# Pan-STARRS - A New Generation Survey Telescope System

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## ABSTRACT

Pan-STARRS is a revolutionary optical/near-IR survey telescope system that is being developed by the U. Hawaii's Institute for Astronomy. The optical design has a 1.8m primary aperture and delivers seeing limited images over a 7 square degree field of view with detectors having 1.4Bn pixels. The final four-aperture system will be sited on Mauna Kea, and a single aperture full-scale prototype is being deployed on Haleakala.

In this talk, I discuss the technical background to the project; the broad range of science goals that the system will address; the design — optics; detectors; data processing pipelines; calibration systems — and the data products.

## 1. INTRODUCTION

Wide-field imaging surveys, as exemplified by the Palomar and UK-Schmidt sky surveys, fell into decline with the advent of CCDs in the '70s. These gave great advantages of sensitivity and linearity but initially allowed only very small fields of view. Subsequent decades have seen exponential growth in area of detectors deployed on astronomical telescopes with a doubling time of about 18 months, conveniently matching the 'Moore's Law' describing the growth of power of computer hardware. At the same time, there has been a major investment in image reduction software required to analyse the data from the ever-growing mosaic detectors.

The current state of the art in wide-field imagers is exemplified by the 300M pixel Megacam on the 3.6m Canada France Hawaii Telescope and the 100M pixel Suprime detector on the 8m Subaru telescope. A parallel development has been the advent of surveys using purpose built dedicated observatories rather than competing for time on facilities developed to serve a broad user base. Examples of these are the Sloan Digital Sky Survey and the 2MASS sky survey.

In recognition of these developments, and in anticipation of further rapid advances in software and detector technology, the US National Academy of Sciences Decadal Review proposed, as a high priority for the next decade, the development of a system they dubbed the "large synoptic survey telescope" with the basic requirement that is should be capable of surveying the entire sky to $\sim 24$th mag in one week, and for which they argued that a 6m class telescope with something like a $\sim 7$ square deg FOV would be adequate. Such an instrument would enable major advances in two separate areas of astronomy:

- Repeated scans of the sky would advance the field of 'time-domain astronomy' — the study of variable, transient or moving objects — with applications ranging from minor planets in the solar system to cosmologically distant transient objects.
- Stacking these images in the computer will, over an extended mission, result in cumulative static sky images from which faint galaxies may be detected, thus enabling a large range of other scientific investigations, mostly in the area of cosmology and including weak lensing and galaxy clustering to probe dark matter and thereby also dark energy.

The Decadal Review was heavily influenced by the 'Dark-Matter Telescope', concept proposed by Tony Tyson and Roger Angel. The DMT concept has undergone various modifications over the years, with consideration of IR imaging and spectroscopic capability being discussed, but is currently conceived of as a 8.4m telescope, for which the proponents adopted the name LSST. Various subsequent reviews have endorsed the LSST concept, mostly in regard to its capability to probe dark energy.

Table 1: Pan-STARRS Specifications

| | |
|---|---|
| optical design | Ritchey-Chretien with 3 element wide field corrector |
| field of view | 7 square degrees |
| collecting area | 4x1.8m apertures |
| detectors | 1.4G-pixel cameras |
| site | Hawaii |
| passbands | $g$,$r$,$i$,$z$,$y$ and $w$ filters |

Pan-STARRS is an alternative way to address the science goals set out by the Decadal Review. It is based on the following:

- The observation that, given a site with excellent image quality such as Mauna Kea, it is possible to reach the 24th magnitude detection limit and scan rate requirements with a smaller net collecting area.
- An aggressive approach to detector design, following the pioneering efforts of the detector group at the IfA who have repeatedly made major advances in cost/performance factors for mosaic CCD arrays.
- That potential savings in telescope costs, and rapid delivery thereof, are allowed by a 'distributed aperture' design using multiple optical systems of modest size.

and has the basic specifications shown in table 1:

The fundamental figure of merit — the product of the collecting area and the field of view —- for Pan-STARRS is $A\Omega = 50$ m$^2$ deg$^2$ which is several times larger than any existing facilities and a factor 6 times smaller than that proposed for the DMT/LSST. Pan-STARRS has also been designed to allow rapid readout in order to allow efficient detection of small objects in the inner solar system (this requires $\lesssim$ 30s integration times to avoid trailing losses and therefore also requires readout on the order of a few seconds to allow good duty cycle; this is another aspect in which Pan-STARRS represents a major advance over existing facilities that have readout times of tens of seconds). With these specifications, Pan-STARRS is capable of detecting objects with $R = 24$ in a 30s integration in median seeing conditions, and is capable of surveying $\simeq 7,000$ square degrees per night, which is adequate to reach the Decadal Review top-level science requirements.

Pan-STARRS is being developed as a phased effort. A single-aperture, but otherwise full-scale system, known as PS1 is being deployed on Haleakala. The telescope has been delivered and is undergoing testing. The next major step will be the installation of the wide-field corrector optics later this year and the deployment of the first large-area detector. This will be a 1/4 scale detector (300M pixels) that will be followed by the first (1.4) Giga-pixel camera (GPC1). Once commissioning is completed, PS1 will embark on a 3.5 year science mission, with operations funded by an international science consortium (PS1SC). The development and construction of the full-scale system (PS4) will parallel the PS1 science mission, with deployment planned for 2010 and with a ten year science mission 2010-2020.

The following sections will describe the science goals and the top-level requirements flow-down, the design and the basic data products.

## 2. SCIENCE GOALS

### 2.1 *Killer Asteroids and Solar System Science*

A prime goal for Pan-STARRS is the detection of potentially hazardous asteroids. Analysis of existing survey results has revealed the distribution in size and orbital elements (semi-major axis, inclination and ellipticity) for objects in the inner solar system. The results allow one to derive the frequency of collisions with Earth as a function of energy, and show that 'major global catastrophes' — those events that result in most live being extinguished — happen every couple of million years or so, while collisions with $\sim$ 300m size bodies, which deliver energies on the order of 1000MT and which would cause massive regional damage, occur roughly every 70,000 years.

While there is considerable uncertainty in estimates of the mortality rate, there is general consensus that this is dominated by the global catastrophe events generated by objects of size greater than about 1km in diameter and which can penetrate the oceans and deliver enough dust to the atmosphere to cause massive crop failures as in the 'nuclear-winter' scenario. While rare, the devastation of such events is so great that, statistically, one is as likely to die from an asteroid strike as in a plane crash. While this risk pales into insignificance as compared to some other forms of natural disasters, it is unique in that astronomical observations and orbital projections allow one to establish whether, in fact, Earth will be hit in the next century or so (it is difficult to to establish if an object will collide on longer time-scales owing to the chaotic nature of solar system dynamics).

This realization led to the congressional 'spaceguard' mandate for NASA to support surveys to catalog such objects. The spaceguard goal is to reach 90% completeness by 2008. Currently, it is estimated that about 50% of km sized objects have been catalogued and that consequently about half of the collision risk that existed at the time of the initial spaceguard debated has now been eliminated.

Once the spaceguard goal is reached, the residual risk will be distributed in roughly equal measure between the residual $\sim 10\%$ of global catastrophe risk and the risk from smaller sub-km impactors. This is where Pan-STARRS comes in; its much greater sensitivity and surveying rate will allow it to detect much smaller objects. Currently, NASA has been tasked by congress to come up with a plan for a mission, or missions, to extend the survey completeness limits down to approximately 140m sized objects, below which size the risk falls because of the protection afforded by the atmosphere. By itself, Pan-STARRS will not be able to attain that goal, but it will, over a 10 year mission, be able to catalog 90% of objects of 300m or greater size, and will detect a large fraction of objects bigger than 140m, thus making major progress toward the new goal. The Pan-STARRS PS1 mission will also, in short order, be able to establish with much greater precision what is the actual risk as there is considerable uncertainty in the frequency of impacts.

In the process of surveying for potentially hazardous asteroids Pan-STARRS will detect massive numbers of objects of all classes in the solar system. Figure 1 shows, for each class of object, how many are currently known and how many will be discovered by Pan-STARRS.

### 2.2 *Stars and the Galaxy*

Pan-STARRS will be a powerful tool for studying the contents and structure of the Milky Way. Currently available all-sky surveys are either restricted to bright stars (Tycho, Hipparcos) or are based on photographic surveys (e.g. USNO-B). The latter reaches limiting magnituded $\sim 20$ and has astrometric precision of around 0".2 (both for random statistical measurement error and for large-scale systematic errors arising from the plate-modelling process) and crude photometric precision. By comparision, Pan-STARRS will reach limiting magnitudes of 24th magnitude and, for somewhat brighter objects, will attain astrometric precision of 5-10 milliarcsec (per visit) and photometry at one hundredth of a magnitude precision or better. Ultimately, Pan-STARRS will itself be surpassed by GAIA, which will achieve astrometric precision at the tens of micro-arcsec level, but GAIA data products are not expected until around 2020 and, until then, Pan-STARRS will be a huge leap forward.

The great astrometric precision will allow determination of parallaxes and proper motions. The former will provide a complete stellar census out to $\sim 100pc$ distances and down to $\sim$ 24th magnitude, and will result in great improvement in our knowledge of the low-mass initial mass function, extending to sub-stellar objects, and is estimated to increase the number of known brown dwarfs by 1-2 orders of magnitude.

Multiple visits over the ten-year mission lifetime will allow the astrometric precision to be further improved, and will result in proper motions for huge numbers of stars with a precision of a few km/s at a distance on the order of a kilo-parsec. This, together with the precise multi-color photometry will be a vital tool for understanding the formation history of the galaxy.

Having tens of visits per passband will allow Pan-STARRS to generate an enormous catalog of variable stars, and thereby allow the use of classical standard candles such as RR Lyrae and Cepheids for probing the structure of the galaxy and its local surroundings.

The star counts and colors will be used to improve models for the thick disk, thin disk and halo structure of our galaxy, which is currently presenting an interesting challenge to conventional theories for galaxy

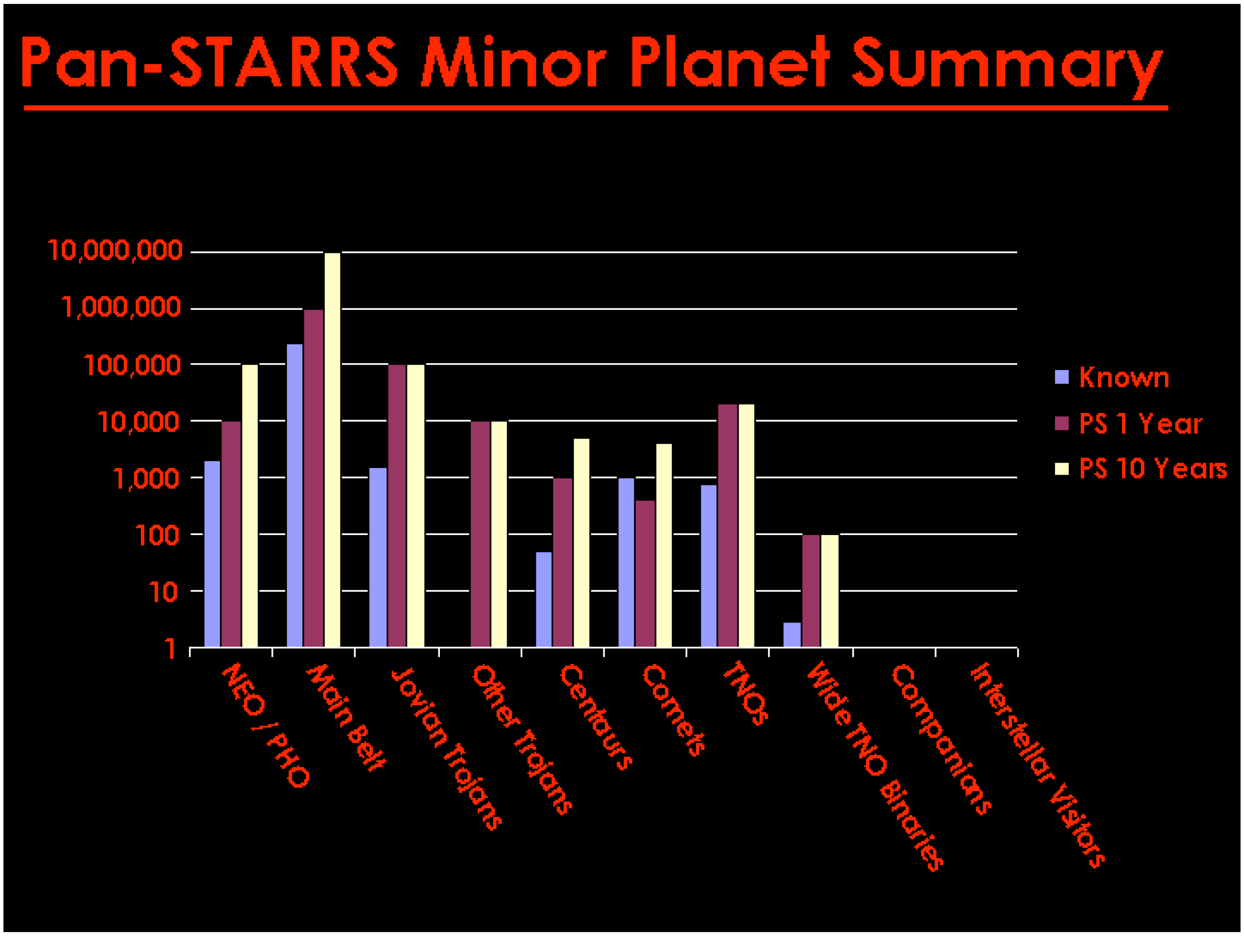


Figure 1: Inventory of minor planets in the solar system. For each class of objects, the bar on the left shows the number of objects that are currently known and the middle and right bars show how many will be detected by Pan-STARRS (PS4) after 1 year and after 10 years. For outer solar system objects, most new discoveries are made in the first year.

formation.

### 2.3 *Static Sky Cosmology*

Pan-STARRS will survey in two major modes; surveys covering 3/4 of the sky and, in addition, deep and medium deep surveys of selected areas, with the latter surveyed at a cadence suitable for detection of supernovae etc. All of these images will be stacked, resulting in 5-passband static-sky images reaching $\sim 26$th magnitude over $3\pi$ steradians and much greater depth in the selected areas.

A major goal for Pan-STARRS is to constrain the cosmological parameters of the Universe, and, in particular, to probe the dark energy. The cumulative static sky images will allow this *via* two complementary approaches: One is weak lensing, which depends on the geometry of the Universe and on the evolution of the dark-matter structure, both of which depend on the dark energy. The other is the evolution of the clustering of the galaxies. As recently shown by the SDSS and 2dF surveys, the galaxy power spectrum displays the wiggles imposed on $\sim 100$Mpc scales by hydrodynamical processes operating at $z \gtrsim 1000$ when the plasma was ionized and, locked together with the background radiation, supported acoustic oscillations generated from the primordial perturbations responsible for structure formation. This has generated intense interest in the possibility of determining the expansion rate using these wiggles as a 'standard ruler'. In addition, the shape of the overall power spectrum is sensitive to the dark energy content.

Both of these cosmological tests are quite challenging. To constrain the amount of dark energy (as characterised by the equation of state parameter $w$) and its evolution at better than the $\sim 10\%$ level requires measurement of the structure, and its evolution, with a precision of better than a few percent. While the statistical precision afforded by e.g. weak lensing is in principle sufficient, realistically the results may be plagued by systematic errors. In this regard, Pan-STARRS will have significant advantages over current surveys, in that the very large area covered and the large number of visits to each field will either allow such systematics to be modeled and subtracted, or, if they prove to be unpredictable, they will tend to decrease as the inverse square root of the number of exposures. For both types of studies, photometry precision is critical in order to provide photometric redshift information which is uniform and has well understood error distribution. In addition, for weak lensing, modeling and control of the point spread function is at a premium.

In addition to these probes of dark energy, the static sky images will be used to generate catalogs of clusters of galaxies, the evolution of which is another complementary probe of cosmological parameters; higher order statistics; and bias and galaxy formation by studying the clustering as a function of color, type and surface brightness. All of the above mentioned cosmological studies will rely heavily on massive numerical simulations of cosmological structure formation.

### 2.4 *Supernova Cosmology and other Variable/Transient Phenomena*

The medium deep survey areas will be visited at a $\sim 4$ day cadence and will discover tens of thousands of supernovae. The SN1a can be used to improve the precision of the Hubble diagram on which the original indication of dark energy was based and, more generally, Pan-STARRS will be a great source of data for studying the physics of supernovae and also for probing the star formation history.

Pan-STARRS will also be able to detect transient and variable objects of many types:

- Active Galactic Nuclei. Variability, as opposed to color, selected samples will shed new light on the properties of such objects, and, additionally, optical variability can be usefully compared to variability at X-ray and shorter wavelengths from surveys such as GLAST.
- Gamma-Ray Bursts. PS will detect many optical counterparts to GRBs and will be able to test theories for GRBs that predict that lower energy photons are emitted in a wider solid angle resulting in so-called 'orphan' events.
- Occultations of stars by planet transits. Pan-STARRS is sensitive to Jupiters around sub-solar mass stars or Earths around brown dwarfs.
- Stellar variability. As mentioned, Pan-STARRS survey cadences will allow detection of stars with all manner of intrinsic variability. In addition, dedicated surveys may be used to probe for microlensing events.

## 3. DESIGN

The major science goals described above lead to the top-level requirements from which the system design has been derived. In some cases these are fairly specific; for example, the inner solar system goals lead to the stringent requirements for short ($\sim 30$s) integration times to avoid trailing losses and correspondingly short read-out times. Other requirements, such as photometric precision, are critical for a wide range of science goals. Given the top-level science-driven requirements, the final design would ideally be derived by an optimization of performance *vs.* price. In practice this is difficult, if not impossible. Instead, in deriving engineering requirements we made considerable use of the known, unavoidable, limitations imposed by the environment and the basic laws of physics and the principle that the requirements for each component should be that the impact on overall figure of merit not be the dominating restriction on performance. While the figure of merit depends somewhat on the precise science goal, a reasonable single criterion is the efficiency for detection of faint point sources, for which the figure of merit is the *etendue* $A\Omega$ divided by the area of the point spread function $\Delta\Omega$ and augmented by the overall quantum efficiency and various 'duty-cycle' effects. This gives a single objective criterion for comparing design performance with costs, and the constraints imposed on the final design were such that, for example, optical design, pixel size etc be allowed to degrade performance by $\sim 10 - 20\%$ but not more, so that the final design allows performance that is reasonably close to the ideal allowed physically given the constraints of seeing limited observations against the sky background.

An overall view of the system components is shown in figure 2 and below we describe the optical design; the camera; the data processing pipeline and finally, the various auxiliary calibration systems.

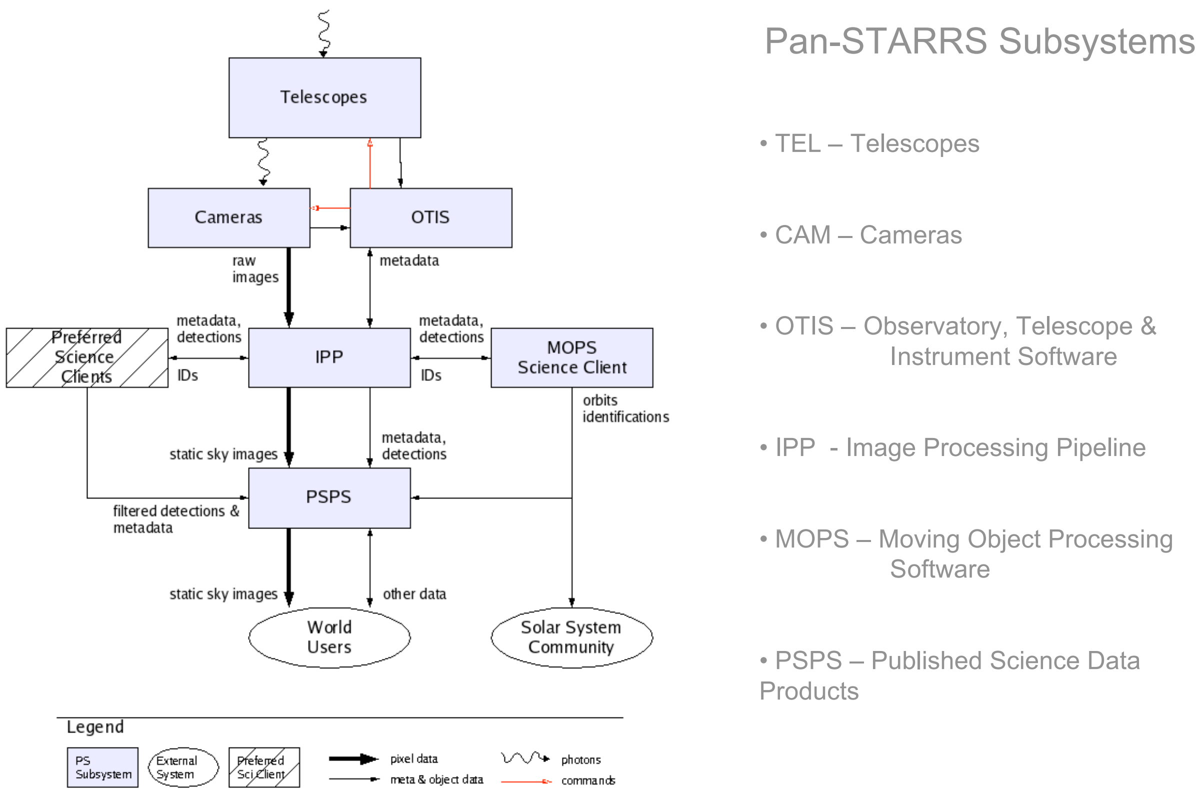


Figure 2: Overview of Pan-STARRS subsystems.

### 3.1 *Optics*

The optical design, shown in figure 3, delivers good image quality over the full 3 degree diameter field of view as shown in figure 4. The filter passbands and overall system quantum efficiency are shown in figure 5 which shows that the performance of Pan-STARRS in the near-IR will be outstanding.

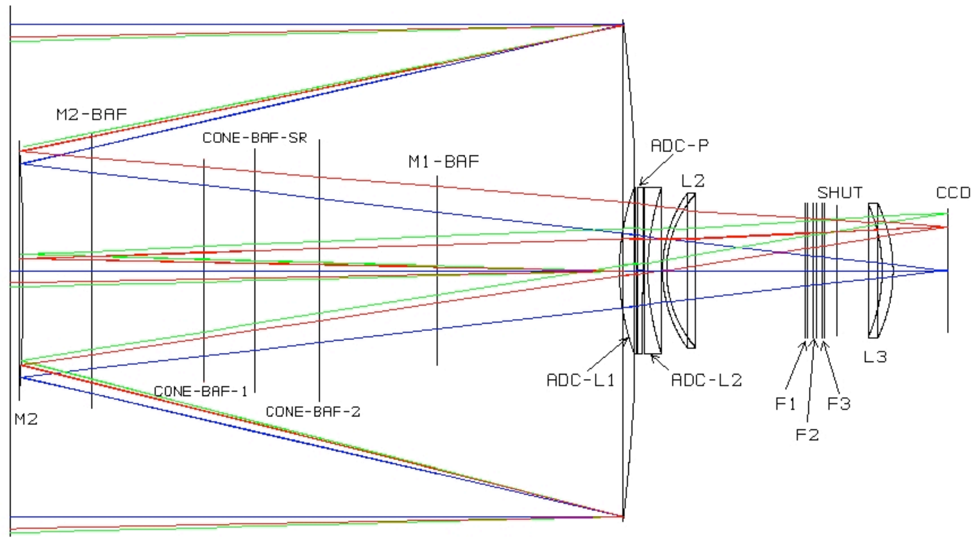


Figure 3: Pan-STARRS optical design is a Ritchey-Chretien with 1.8m diameter primary and 0.9m diameter secondary mirrors and a three element wide field corrector consisting of refractive elements L1, L2, L3. The PS1 prototype will initially have a monolithic L1, but the design is such that this can later be replaced by a multi-element lens containing a prism with siloxane fluid between the glass elements to implement a atmospheric dispersion compensator.

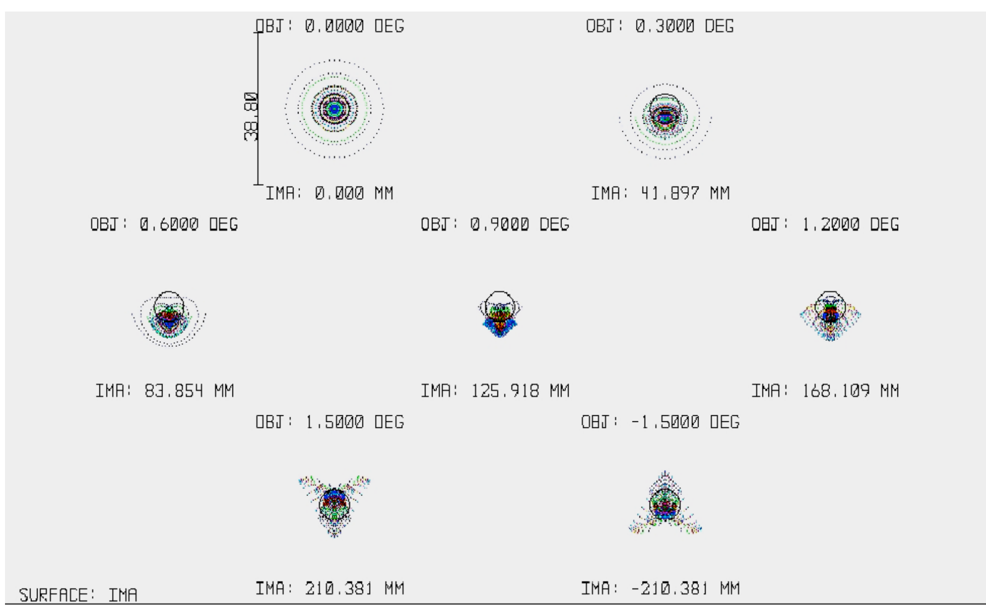


Figure 4: Spot diagrams for various field positions for the Pan-STARRS optical system. For reference, the bar at the side of the upper left diagram is one arc-second, so at all field positions any aberration from the telescope results in negligible broadening of the point spread function under realistic seeing conditions.

3.2 *Detectors*

The large field of view (7 square degrees) and the high quality seeing provided by Hawaiian sites leads to the requirement of approximately 1.4 billion pixels per focal plane for adequate sampling. The physical pixel size is 10$\mu$m, corresponding to an angle of 0".26. Together with the requirement of short ($\sim$ 5s) readout commensurate with 30s exposure times this requires a massively parallel architecture. The solution adopted is an "array of arrays" in which the focal plane is constructed from a 8x8 chess-board of 5cm square monolithic devices and where each device is an 8x8 chess-board of independently addressable "cells", each of size 600x600 pixels. To meet the read-out rate with acceptable read-noise requires that 8 cells on each device be read simultaneously, so overall there are 512 parallel read-out channels. In addition to parallelization of data flow, a further advantage of the array design for the detectors is that they allow enhanced yeild. In conventional designs, a single flaw in manufacturing can render an entire device non-functional whereas with the PS devices only that cell which contains the flaw will be affected. Since regions around bright stars will necessarily be lost for science, and the surveying strategy involves combining multiple images, losses of small regions do not seriously affect the overall system performance.

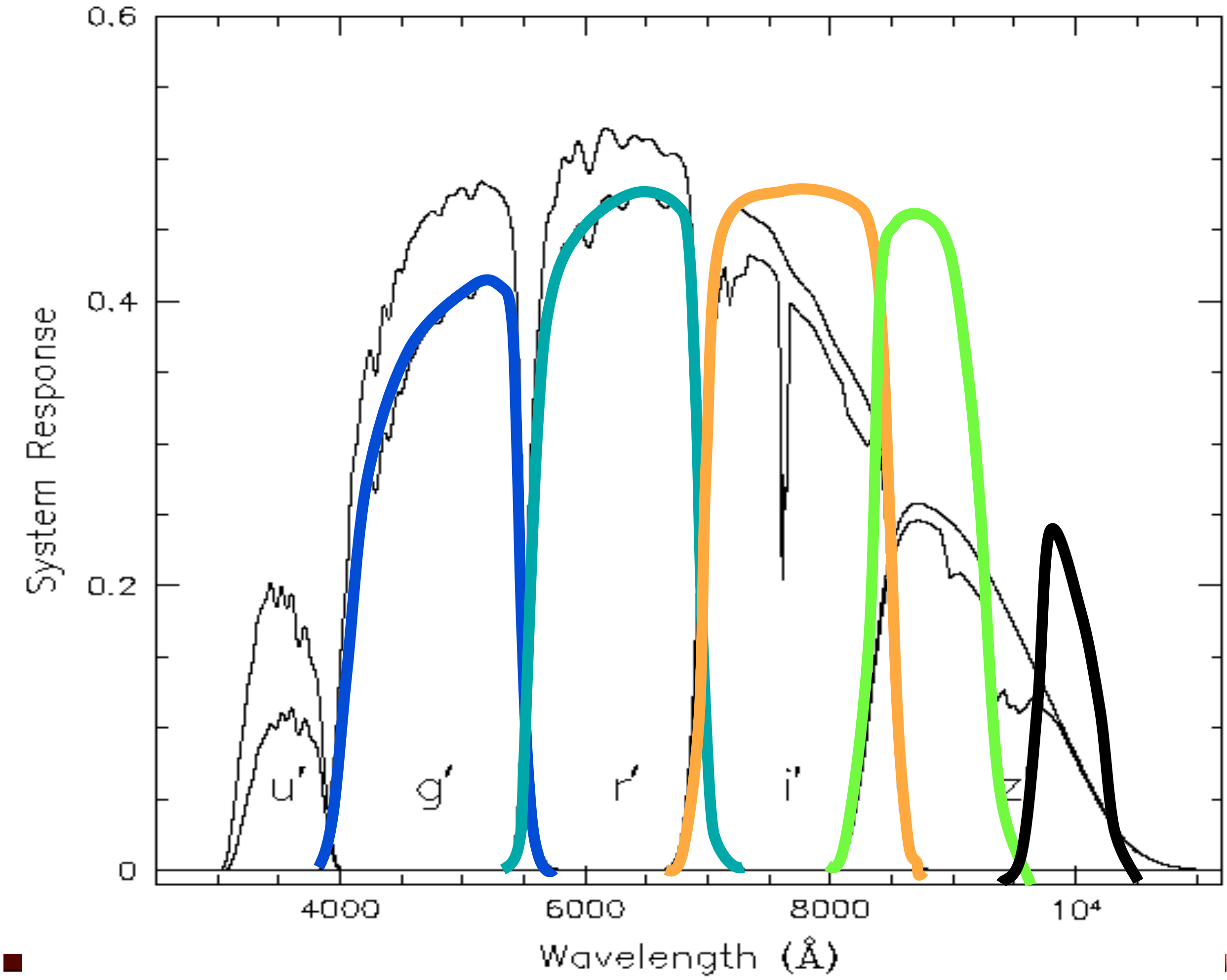


Figure 5: Pan-STARRS passbands and system quantum efficiency. The $g$,$r$,$i$,$z$ filter passbands have been designed to closely match those used by the Sloan Digital Sky Survey. An early design decision was to dispense with $u$-band imaging as it imposed difficult constraints on the optics, and the science goals are weighted more towards the red-end of the spectrum. The detectors are thick deep-depletion devices that allow excellent sensitivity out to the cut-off imposed by silicon.

The detectors feature 'orthogonal transfer' (OT) technology. In conventional devices, there are 3 gates per pixel, allowing the charge to be transferred in one direction during read-out. In an OT device there is an extra gate, and this allows charge to be 'clocked' in 2 dimensions. This technique, developed by John Tonry and implemented on the OPTIC camera used on the UH 88" telescope, allows on-chip fast guiding which can cancel the effects of wind shake and ameliorate some of the effect of atmospheric seeing. The OT capability is nicely integrated with the array design of the detectors. Any cell that happens to contain a bright star can have the region around the star read-out at video rates in order to monitor the motion of the star's centroid. The information from these guide stars is analyzed and used to generate guide signals to move the charge in the other cells to track the the motion of the images.

### 3.3 *Image Processing Pipeline and Data Products*

Pan-STARRS will generate data at the rate of terabytes per night, and an image processing pipeline (IPP) has been developed to process these data in near real time. The IPP will perform all of the usual steps involved in flat-fielding and sky background subtraction. In addition, it will perform registration to map pixel coordinates to sky coordinates and pixel values to intensity in order to generate cumulative static sky images and difference images from which transient, variable and moving objects can be detected.

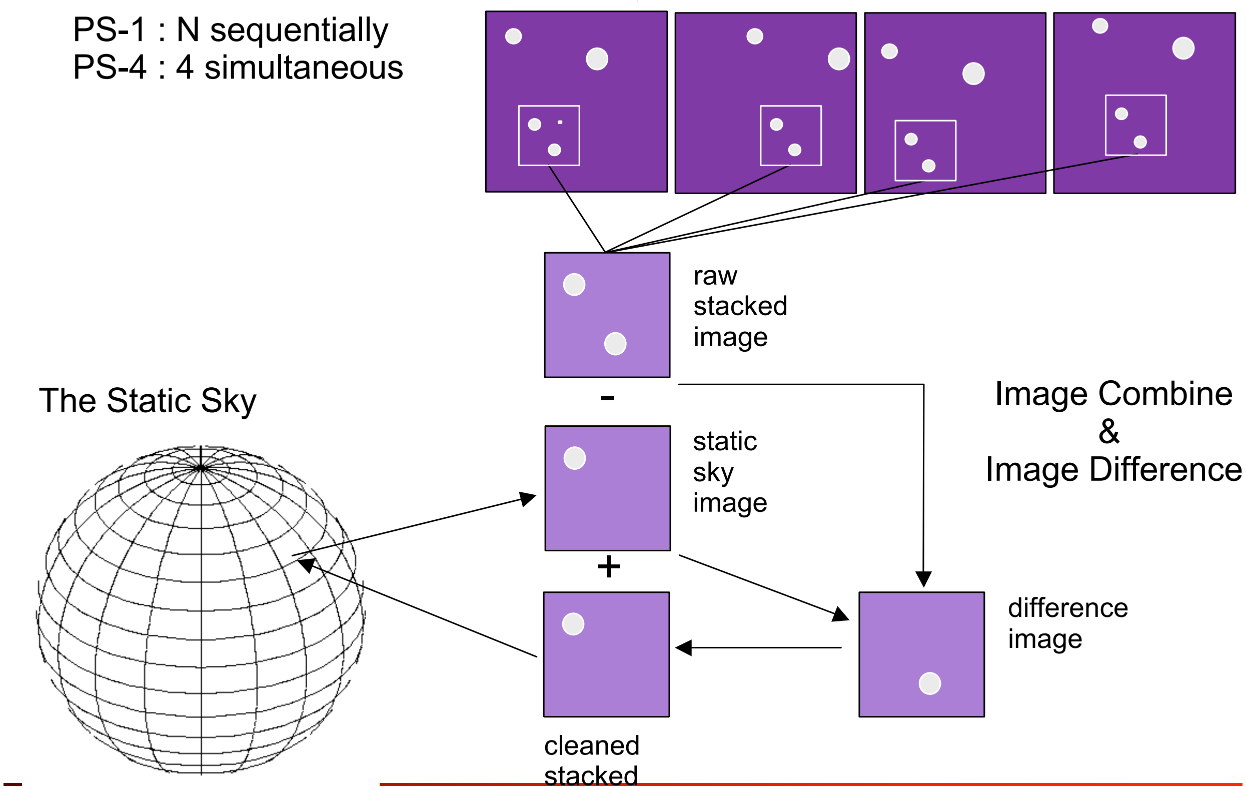


Figure 6: Pan-STARRS image processing pipeline. The IPP has been designed to take as input a set of 'dithered' images of a patch of sky — for PS4 these would typically be taken simultaneously with the 4 separate optical systems. After independent flat-fielding and sky subtraction these images are combined, with cosmic ray rejection, to form the current image of the patch. A PSF matched template is then generated from the static-sky data store and is subtracted to generate a difference image that is blank, aside from transient, variable and moving objects. Finally, the stacked image will have the objects detected in the difference image removed, and the result will then be accumulated into the static sky.

The IPP will result in the following basic data products:

- Instrumental catalogs. These are generated from the flat fielded and sky subtracted, but unwarped, images. These are useful for projects requiring the utmost in astrometric and photometric precision (whereas warping the images to sky coordinates necessarily involves some loss of information). These catalogs will include postage stamp images for brighter objects to allow advanced image processing techniques such as de-aliasing and de-convolution.

- Static sky images. These consist of at least a 'signal' and 'exposure' map. In addition, there will be some redundancy built in to allow for recovery from data corruption.
- Static sky catalogs. Photometry and astrometry of objects detected in the static sky images. These will include the time history of magnitude measurements to allow study of nuclear variability of galaxies.
- Difference image detection stream. These may be augmented by the recent history of difference images in order that one can ask what a source did prior to triggering detection.

### 3.3 *Calibration and Control of Systematics*

Pan-STARRS requirements are to reach 1% photometric precision, and the goals are to do even better. Similarly, science goals such as weak lensing require careful control of the point-spread function. In order to achieve these demanding goals the observatory will be equipped with a number of auxiliary systems to provide calibration and control of image quality.

Regarding photometric calibration, Pan-STARRS will depart from the standard procedure or simply observing Landolt standard fields occasionally. Absolute calibration of the detectors will be performed in the lab before deployment. A 'calibration screen' fed by a tunable laser will be used to provide absolute measurement of the total system throughput. These measurements will be made frequently in order to identify any changes in QE. An imaging sky probe (similar to that used on CFHT) will piggy-back on the telescope and will monitor atmospheric transparency using bright stars and will also monitor the air-glow. A spectroscopic sky probe is planned. This will take low dispersion spectra of both stars and air-glow. These data will be analyzed using the MODTRANS software to generate detailed models for the atmosphere and hence a high spectral resolution model of the air-glow — from which fringe frames can be synthesized — and of the atmospheric transmission — which can be folded through the transmission function to determine photometric zero points. The atmospheric dispersion compensator will improve the precision of photometry, especially in regions of high stellar density. A high priority for PS1 is to generate a dense grid of astrometric and photometric standards. The large number of independent exposures will help overcome many sources of systematic errors.

Regarding control of the PSF, PS will feature two wave-front sensing systems. One of these is a deployable Shack-Hartmann system which can be used to diagnose problems. The second is a curvature sensing system similar to that planned for the VISTA telescope that will operate continuously to provide wave-front sensing. These measurements will be used to actively control the collimation and alignment of the telescope and to control the figure of the primary, which is supported on a network of pneumatic supports. Other features that will improve the PSF quality are the use of orthogonal transfer devices, which can remove quadrupole anisotropies arising from e,g, wind-shake, the ADC, and as with photometry, the ability to combine large numbers of images will help.