PS1 and the PS1 Science Mission

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ABSTRACT

The Pan-STARRS Telescope No. 1 (PS1) is a prototype telescope for a large optical synoptic survey telescope system; the Panoramic Survey Telescope and Rapid Response System. PS1 is a 1.8m wide field telescope with a 7 square degree field of view and an unpreceeedented 1.4 Gigapixel Camera located on the summit of Haleakala, Maui, Hawaii. PS1 will be able to scan the entire visible sky to approximately 23th magnitude in less than a week, and this unique combination of sensitivity and cadence will open up many new possibilities in time domain astronomy and address a wide range of astrophysical problems in the Solar System, the Galaxy, and the Universe. A description of the PS1 capabilities, science drivers, and the PS1 Science Reference Mission will be presented. The main goals of the Reference Mission are a 5 bandpass (*grizy*) 3 pi steradian photometric and astrometric survey; a 5 bandpass $\sim$ 50 square degree medium deep survey and a single wide band ($w = g + r + i$) ecliptic plane survey primarily for Solar System studies and Near Earth Asteroids. This project includes contributions from The Institute for Astronomy, the Maui High Performance Computing Center, SAIC, AFRL, and Lincoln Laboratory.

1 BACKGROUND

The Pan-STARRS Telescope No. 1 (PS1) is 1.8 meter diameter telescope under construction on Haleakala with wide field optics, a 7 square degree field of view, a 1.4 Gigapixel Camera with Orthogonal Transfer Arrays. These OTAs provide a 10 to 20 percent improvement in PSF width. Commissioning of PS1 will commence in the summer of 2006, and after a full Operational Readiness Review by the PS1 Science Consortium, we expect to begin a 3.5 year Science Mission starting approximately March 1, 2007.

PS1 is a research and development project built as a prototype for the complete Panoramic Survey Telescope and Rapid Response System or Pan-STARRS project, or PS4, with 4 times the collecting area and four cameras.

The primary science design drivers for PS1 from the PS1 Mission Goals Statement are:

- Precision photometric and astrometric survey of stars in the Milky Way and the Local Group;
- Surveying our Solar System, including searching for Potentially Hazardous Objects amongst Near Earth Asteroids;
- New constraints on Dark Energy and Dark Matter;
- Exploration and categorization of the astrophysical time domain, including, but not limited to, explosive transients, microlensing events in M31, and a transit search for exo-planets; and
- Providing a development platform for prototyping PS4 components, subsystems, and survey strategy.

These goals drive the design and engineering requirements, but do not begin to cover the vast array of solar system, galactic, extragalactic, and cosmological studies that can be done with the PS1 data products.

The PS1 field of view with good image quality is 3 degrees in diameter. the 1.44 Gigapixel camera fills this circular FOV and more, with detectors outside the 3 degree circle for WFS and optimization of overlapping regions. The fill-factor will be approximately 90 percent: 9% from internal streets, 2.5% from external gaps, 2.5% from dead cells (this should be compared with 5% for E2V chips). There will be an additional 1 to 2 percent loss from streak removal of objects inside geosynchronous orbit. Simulations with a modified version of the LSST simulator imply a maximum observing efficiency of 70% of clear time. For large regions of the sky, the observing footprint will be laid down in an approximately hexagonal spacing due to the circular field of view. This implies 20 percent area overlap from adjacent hexagonal spacings as large regions of the sky are mapped. On average, 35% of the nights on Haleakala are photometric, and an additional 30 percent are useable with either very low extinction or more than 60% of the sky clear of clouds as shown by the IR cloud camera. PS1 will be essentially sky noise dominated in 30 seconds in i, z, y, w bands, there will be some contribution from read noise in g for maximum allowed 6 electron rms read noise. This document is a summary of important revisions of the concepts that went into the initial PS1 Design Reference Mission (PSDC-230-001-00). The PS1 Design Reference Mission will be subsequently revised (by Dec 31, 2006) to reflect the Mission as it is described herein, and including detailed scheduling simulations of the PS1 Mission.

1.1 PS1 Mission Overview

In this PS1 Mission Concept Survey we detail the system sensitivities, and an overview of the PS1 Surveys as currently envisioned in order to meet the PS1 Mission Goals Statement. The PS1 Mission Concept has gone through a large number of iterations with the intent of optimizing the overall scientific return for the the PS1 Mission Science Goals. There are many competing aspects to this, and no one Mission Concept will uniformly satisfy all science goals, but the results of our preliminary research so far suggest we have found something close to an optimum Conceptual Survey. The full details and comparisons with alternative suggested strategies will be presented in the PS1 Design Reference Mission. This shorter document is to inform the PS Project and PS1 Science Consortium of the current status of our research on finding a nearly optimal solution for maximizing the science goals of participants in the PS1 Science Consortium.

The current PS1 Mission concept is based on a limted set of simulations with our modified version of the LSST simulator, and hand calculations. The PS1 DRM will present detailed results of these simulations. We are developing related interactive code for real time scheduling and computer assisted scheduling for PS1. Fully automated scheduling is not a requirement for PS1.

2 PS1 SENSITIVITIES

The parameters required to estimate the sensitivity of PS1 in each band-pass are given in Table 1. Details of the PS1 filter specifications are given in PSDC-330-002.

The signal-to-noise ratio for a point source (or a trailed NEO) depends on the total throughput of the atmosphere, the telescope optics, and the sensitivity of the camera detector in a given pass-band. The effective sensitivity is characterized by the magnitude m_1 that produces $1e^-$/sec/pixel. The signal from a given source of total apparent magnitude m, in exposure time t seconds, and assuming PSF fitting photometry, is:

$$S = t \times \frac{1}{2} \times 10^{-0.4(m-m_1)}.$$

The noise N comes from a combination of sources of variance: the Poisson noise of the source counts, $\sigma_P^2 = 0.5 \times 10^{-0.4(m-m_1)}t$; the variance from the sky background, $\sigma_S^2 = \frac{\pi}{4}\omega^2 \times 10^{-0.4(\mu-m_1)}t$, where ω is the FWHM of the PSF in arcseconds, and μ is sky brightness in magnitudes per square arcsecond; the variance from the read-noise of the detector $\sigma_{RN}^2 = \frac{\pi}{4}\omega^2 \times A \times N_{read}^2$ where $A = 3.846$ pixels/arcsec^2 for

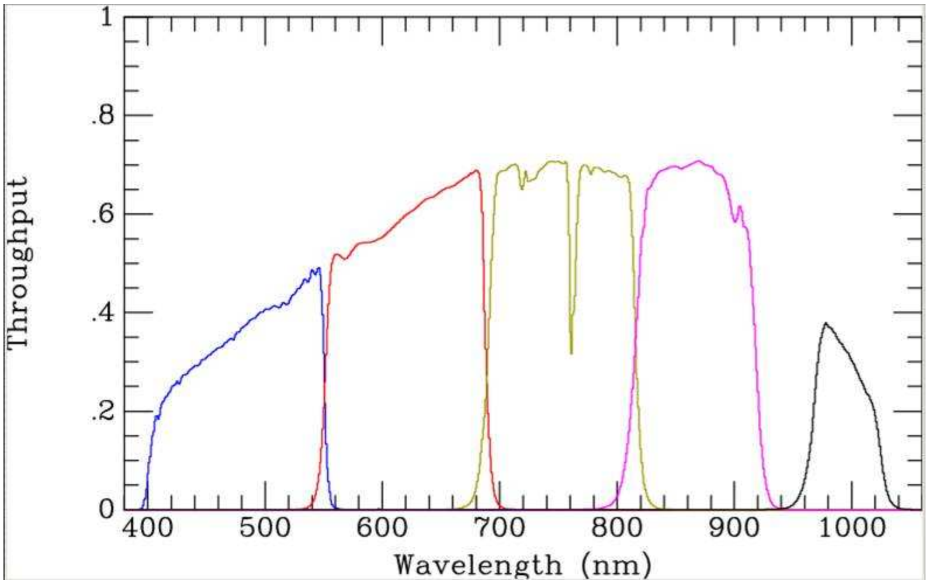

Table 1: *The parameters required to estimated the sensitivity of PS1 in each band-pass given. The magnitude that produces 1 electron/sec/pixels is computed assuming 75 micron thick chips, aluminum coatings on the mirrors, an effective loss of 0.35 area from secondary mirror blockage and diffraction from baffles and secondary mirror support structure. The average sky brightness μ in magnitudes per square arcsec at Haleakala assumes the Wainscoat light pollution factor in g and r band. A mean air mass of 1.4 is assumed.*

Filter	Bandpass (nm)	m_1 AB mag	μ AB mag/asec^2
g	405–550	24.90	21.90
r	552–689	25.15	20.85
i	691–815	25.00	20.15
z	815–915	24.63	19.26
y	967-1024	23.03	17.98
w	405–815	26.22	20.63
$w_\odot$	405–815	26.22	20.67

0.26 arcsecond pixels, and N_{read} is the read noise of the detector; the variance from any Radio Frequency Interference (i.e. an increase in effective read-noise that is seen at the summit of Haleakala, but not in the laboratory[1]) [1] $\sigma^2_{RFI} = \frac{\pi}{4}\omega^2 \times A \times N^2_{RFI}$; the variance due to dark current D counts/sec $\sigma^2 D = \frac{\pi}{4}\omega^2 \times A \times Dt$); and the variance due to the dilution of the signal over a larger area due to motion of an NEO during an exposure, where these trailing losses are small, is $\sigma^2_T = \frac{1}{6}(tR_{NEO}/\omega)^2(\sigma^2_S + \sigma^2_{RN} + \sigma^2_{RFI} + \sigma^2_D)$ where the

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[1] The broadcast towers which produce the bulk of the RFI at Haleakala will be re-located by the time of the PS1 Science Mission. Nonetheless, there will be remaining sources of RFI at the summit, the effect of which is difficult to determine in advance of commissioning.

average trailing rate for NEO's is taken to be $R_{NEO} \approx 0.02$ arcsec/second, or half a degree per day. The signal-to-noise ratio for a given observation is then:

$$S/N = S/\sqrt{\sigma_P^2 + \sigma_S^2 + \sigma_{RN}^2 + \sigma_{RFI}^2 + \sigma_T^2 + \sigma_D^2}$$

where each individual variance is given in the text above.

3 PS1 MISSION SURVEYS

Table 2: *The PS1 Mission Concept Surveys and time distribution.*

PS1 Surveys	Filters	Percent time
3 π Steradian Survey	g, r, i, z, y	56
Calibration Fields	g, r, i, z, y	2
Medium Deep Survey	g, r, i, z, y	25
Solar System "Sweet Spot" Survey	r	5
Stellar Transit Survey -"PanPlanets"	i	4
Microlensing in M31 "Pandromeda" Survey	g, r, i, z, y	2
Principal Investigator Discretionary Time		6

As put forth in the PS1 Mission Goals Statement, PS1 wishes to maximize the scientific output of PS1. The Mission Goals are diverse, and require detailed survey strategies in terms of cadencing, duration, and revisits. Simulations show that increasing diversity in the survey strageties lead to increasing observing inefficiencies. The effect is complex, but the increasing in-efficiency is largely due to cadence-driven accumulated re-visiting requirements. A full discussion will be given in the PS1 Design Reference Mission document. Presented here is the conceptual design of the PS1 Mission based on the PS1 Mission Goals Statement and initial studies with the modified LSST simulator. The Mission Concept outlined here is schematic, and serves largely as the input to the detailed studies being carried out for the PS1 Design Reference Mission document. The rules for adjusting and changing the DRM are laid out in the PS1 MOA and PS1 Science Consoritium Policy documents, and changes to the survey strategy will be considered periodically by the PS1 Board as the PS1 Mission progresses.

The PS1 Concept Mission Surveys and their approximate observing time distribution is shown in Table 2.

3.1 3 π Steradian Survey

To meet the PS1 Science Goals, including the all sky precision photometric and astrometric survey required for high fidelity image registration and subtraction, we have found from survey simulations (using a modified version of the LSST simulator) that a single all sky 3π steradian survey is much more efficient than two separate surveys, e.g. a astrometric and photometric survey that requires the available photometric time, and a separate Opposition Survey for NEOs. By combining the time for these two surveys into a single all sky survey the telescope can be scheduled significantly more efficiently than for two distinct surveys. This approach guarantees that the NEOO search program gets all the photometric time on Haleakala. It also extends the NEOO search program to the celestial pole, as opposed to +40 ecliptic latitude, and more than doubles the total time that can be spent observing at the appropriate NEO cadence. By matching the depth of each pass-band, and by using the appropriate pass-band for a given lunar phase, the efficiency is further increased, as bright time would severely limit the sensitivity of a wide bandpass w filter. With this strategy, 60 percent of PS1 observing time can be spent on an opposition survey optimized with the NEO cadence.

For the 3π Survey, the entire sky available from Hawaii will be surveyed in 5 bandpasses from a declination of -30 to the North Celestial Pole. This is 3/4 of the entire celestial sphere, or 3π Steradians. This survey is expected to use approximately 60 percent of the total observing time, and address aspects of all of the the primary science goals above. More than half of this time is expected to be photometric. It remains to be seen how well we can combine data from nights with sparsely distributed clouds ("photometric in patches") and nights with thin cirrus, with the truly photometric nights, but simulations show the best approach is is to maintain a constant survey strategy, rather than separate a photometric survey with cadence requirements from a non-photometric survey with cadence requirements.

The entire sky can be surveyed with the exposure times listed in table 1, with 4 visits per year in each of three bands g, r, i, z, y. Each night that a given field is observed, it is visted twice, with the pair of images separated by a Transient Time Interval, (TTI) of approximately 30-60 minutes to distinguish moving solar system objects from stationary transient objects. Although not planned at this time, we have examined the option of using back-to-back exposures to improve the "instantaneous" sensitivity to moving objects, and this may be a strategy that should be revisited after experience with the PS1 system and further algorithm and code development.

By choosing sky regions, bandpasses, and cadences carefully, and accounting for the historical weather pattern, we expect to be able to cover the entire sky north of -30 degrees declination 4 times in each band pass g, r, i, z, y every year. We are proposing for a 3.5 year mission on the assumption that with the very tight scheduling of the diverse surveys, and the know difficulties with starting a survey with a new telescope, that the system is not likely to achieve top observing efficiency immediately.

The basic observing strategy is to get 2 vists (exposures) to a given field in a single night per lunation in each of five colors. Every field is then observed over two lunations, giving 4 vists (exposures) per color per year. The g, r, i bands are balanced to provide approximately uniform depth for mean asteroids, so that there are a minimum of 3 pairs of observations per lunation, and two lunations per year, or six epochs for orbit determination per year in the opposition survey. The y band observations are taken in the areas adjacent to the opposition survey for scheduling reasons, and will give additional linkages for bright objects. The z band is taken in twilight for optimizing the parallax detections, the seeing at twilight is typically worse than a few hours after twilight, so the evening z band limiting magnitude may suffer from this.

More than half of the clear time is expected to be photometric. It remains to be seen how well we can combine data from nights with sparsely distributed clouds ("photometric in patches") and nights with thin cirus. The stacking of images, and the number of stacked images that will be produced and saved are a Science Consortium and storage issue. It may be desirable to produce more than one static sky image, where the the combined stacked images are combined by different algorithms to optimize one or more of the following: image quality (seeing), photometric accuracy, image differencing, sensitivity to point sources, sensitivity to extended surface brightness, preservation of morphology, preservation of astrometric accuracy.

For Solar System studies, it is important to note that the the mean color of asteroids is (g-r) = 0.44, and (r-i)=0.14, or solar color. The depths given for trailed NEO's (0.5 degree per day) show that for an asteroid of solar color, the 5 sigma detection limit in each band, given its exposure time and the trailing loss associated with that exposure time, is the same in each band. To convert to units familiar to the NEO and asteroid community, Johnson V band is, for solar colors, approximately $V = r + 0.4$, thus the trailed NEO single exposure sensitivity is equivalent to $V = 23$ in g,r, and i bands.

For objects moving significantly slower than 0.5 degrees per day, the point source sensitivity should be used. For NEOs with trailing losess, and putting in the requirement that tracklets that require two

Table 3: *Estimated PS1 sensitivities for single exposures in the 3π survey. The tabulated numbers use the above equations and assume 75 micron chips, aluminum coating, effective loss of 0.35 area from secondary mirror blockage and diffraction from baffles and secondary mirror support structure. The average sky brightness μ at Haleakala assumes the Wainscoat light pollution factor in g and r band, and an average air mass of 1.4 is assumed. The FWHM is taken to be* 0.78 *arcsec, or three pixels assuming OTA improvement. A read noise of 5 electrons rms is assumed, and zero contribution from RFI.*

Filter	m_1 AB mag	μ AB mag/asec^2	exposure time/visit sec	5σ trailed NEO/visit	5σ pt. source per vist	visits in one night	visits per year	visits per 3 yrs	5σ pt. source in 3 yrs
g	24.90	21.90	60	23.06	23.24	2	4	12	24.59
r	25.15	20.85	38	22.62	22.70	2	4	12	24.05
i	25.00	20.15	30	22.48	22.59	2	4	12	23.94
z	24.63	19.26	30	21.53	21.59	2	4	12	22.94
y	23.03	17.98	30	210.07	20.12	2	4	12	21.47

detections, this means the PS1 sensitivity, for the given exposure times and assumptions quoted in Table 2, are for the "discovery of tracklets" is equivalent to a 5 sigma limiting magnitude of V=22.8.

For galactic and extragalactic studies the 3 year stacked point source sensitivity is slightly optimistic because it assumes all the time is photometric when there will be some data in the total stacked image from less than photometric conditions, and thus should be considered uncertain by a few tenths of a magnitude.

3.2 Calibration fields

Every hour during photometric conditions, but only during photometric conditions (as determined in real time by the Imaging Sky Probe) the 3 π survey will visit one of 20 calibration fields. Filter changes as required will occur on calibration fields, For example after an hour in I band, the telescope will slew to the nearest calibration field, take a 30 second I band exposure, if necessary for the next survey field it will change filters on the calibration field, take an image in the new filter, and then proceed. The calibration fields will thus compose a moderately deep set of images obtained in all colors on a regular basis. Some of the calibration fields have to be standard photometric fields to obtain consistency with other calibrations. But any field can in principle serve as a calibration fields, and all of the Medium Deep Survey (described below) fields will also serve as calibration fields. These fields can be used for a wide range of auxillary science projects, the primarily requirement is that the overall distribution is approximately uniform across the sky, and that some are standard photometric fields. The Calibration fields are expected to use 2 percent of the photometric telescope time.

The suggested calibration fields are listed in the appendix.

3.3 Medium Deep Survey Survey

The Medium Deep Survey is 12 footprints spaced around the sky optimized for studies of SnIa with five colors in a four day cadence reaching a optimum depth for measuring the epoch of re-acceleration and placing limits or detecting cosmological quintessence. The nightly depth is chosen to detect SnIa at $z = 0.8$. The stacked images constitute an 84 square degree survey capable of detecting L^* evolved galaxies at redshift $z = 2.0$.

Table 4: *Estimated PS1 sensitivities for the Medium Deep Survey. The tabulated numbers use the same assumptions as those for the 3pi Survey.*

Filter	Bandpass (nm)	m_1 AB mag	μ AB mag/asec^2	exp time sec	5σ point source in 4 nts	5σ point source in 1 yr	5σ point source in 3 yrs
g	405–550	24.90	21.90	3×240	24.76	26.68	27.27
r	552–689	25.15	20.85	3×240	24.43	26.34	26.93
i	691–815	25.00	20.15	6×240	25.43	27.34	27.93
z	815–915	24.63	19.26	6×240	23.76	25.67	26.26
y	967-1024	23.03	17.98	6×240	22.32	24.23	24.82

3.4 Sweet Spot Survey

Each lunation approximately 500 square degrees in each of two "sweet spots" will be observed twice a night, separated by approximately a one half hour Transient Time Interval. This region is currently scheduled to be re-observed three times a lunation. Without an ADC, this must be done in a normal filter, the greatest sensitivity for solar colors in the least amount of time is the $i$band. This will have the same equivalent $V = 22.8$ for "discovery tracklets", not point source detection. However, since the observations will be at high airmass, one expects greater losses from extinction and seeing.

3.5 Stellar Transit Survey

The goal of the stellar transit survey, or "Panplanets" is to find ≈ 100 Hot Jupiters by detecting the transit of such an object in the light curves of millions of stars visible in the proposed survey fields.

Each stellar transit survey campaign in the "PanPlanets" Survey covers three adjacent fields or 21 square degrees, with each field having 2 minutes of time, and repeating in 6 minutes. Each campaign is to be scheduled for 120 hours per year, and it is expected that this time will be reduced by the same fraction as that due to weather and average observing efficiency factors as the rest of the PS1 Mission.

The observations will be scheduled in 3 hours contiguous blocks per transit night unless it can be conclusively demonstrated that shorter contigous blocks produce superior relative photometric data.

Three campaigns in the PS1 Science Mission are expected, the first two scheduled consecutively over the course of the Mission, and third as efficienctly as possible following the other two at the end of the Mission.

The goal is to reach 1 to 0.5 percent relative photometry, with the goal of discovering ≈ 100 Hot Jupiters.

3.6 Microlensing in M31

Self-lensing provides a unique way to measure the stellar mass function in the bulge of M31 down to the faintest stars and brown dwarfs, where direct resolved photometry is not possible. The proposed dedicated survey to micro-lensing in M31 is expected to produce at least 300 self lensing events per year, with 50 MACHO events if the dark halo is 10 percent MACHOs.

Optimum strategy is 2 vists per night of observation, separated by up to 5 hours, with approximately 360 seconds total integration per visit in r band for a minimum of 10 consecutive weeks. Additional colors shall be included for a total time up to 720 seconds every night for 5 months per year.

4 PS1 PRECISION PHOTOMETRY

Great effort is being placed into achieving a new level of astrometric and photometric precision and accuracy. This includes a "monochromatic" 1.8 meter calibration unit, simultaneous meta-data from co-aligned imaging and spectrographic instruments, and extensive meteorological sensing and modeling to to determine atmospheric transmission (and emission). (The Imaging Sky Probe is under construction, the Spectrographic Sky Probe will require consortium support.)

The PS1 photometric requirements are 10 millimagnitude relative photometry across the sky, with a goal of 5 millimagnitudes in selected areas. The PS1 astrometric requirements are 10 mas relative astrometry, and 30 mas absolute astrometry. In both cases these requirements refer to objects bright enough such that the error in their detection is dominated by photon statistics from the source, not the sky.

The Image Processing Pipeline will remove the instrumental signature from the data, and warp it onto a 0.2" pixel sky image, subtract a pre-existing static sky image with PSF matching, and detect objects in the difference-image with a latency less than 15 minutes.

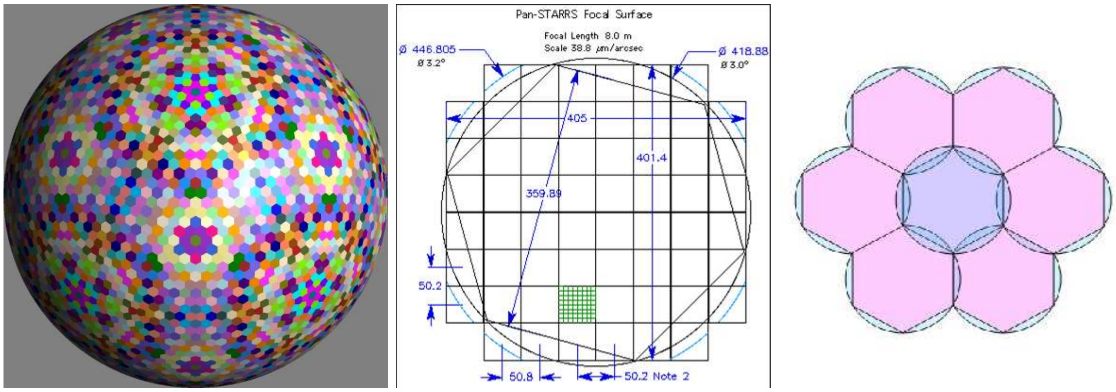

Figure 1: Left: Outside view of the celestial sky tesselated into 6252 fields. Of these fields, 5464 have boresight centers ≥ -30 degrees Declination. Center, the 3 degree field of view of PS1 with an inscribed hexagon of 5.84 square degrees. Right, the twenty percent overlap from a single tesselation due to the circular field of view.

5 Acknowledgements

Most of this document contains information from PSDC-230-001-00, or Version 00 of the PS1 Mission Concept Statement by K.C. Chambers.

The Pan-STARRS project includes contributions from The Institute for Astronomy, the Maui High Performance Computing Center, SAIC, AFRL, and Lincoln Laboratory.