Pan-STARRS – The PS1 & PS2 Wide Area Survey for NEOs

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ABSTRACT

The Panoramic Survey Telescope and Rapid Response System or Pan-STARRS is a wide field sky survey system developed at the University of Hawaii that now includes both the PS1 and PS2 telescopes and extensive cyber-infrastructure for image processing, machine learning, and very large hierarchical databases. The emergent Pan-STARRS infrastructure is described together with the survey goals for the next five years of Pan-STARRS static sky and time domain science. PS1 has produced the premier photometric sky catalog with better than 7 milli-mag accuracy across the sky and with the best tie to an absolute AB photometric calibration. The catalog for mean positions has been placed on the Gaia frame, and thus extends the Gaia frame to 23rd magnitude. The Pan-STARRS catalog has thus becomes the standard reference for astronomical photometry. Pan-STARRS leads the world in discovery of Near Earth Objects, Supernovae, and rare but important objects including the first Interstellar Object, binary neutron star mergers, and super-luminous supernovae. Pan-STARRS together with the CFIS survey will provide the galaxy photometry necessary for the Euclid Mission to perform the tomography of the dark matter content of the universe. With the addition of the PS2 facility to the Pan-STARRS Observatories we have doubled our survey power and discovery rates.

1. INTRODUCTION

The Panoramic Survey Telescope and Rapid Response System — Pan-STARRS — is an innovative wide-field imaging facility developed at the University of Hawaii's Institute for Astronomy (IfA) [1,2]. Approximately 80 percent of the construction and development funds came from the US Air Force Research Labs (AFRL) in response to a Broad Area Announcement "to develop the technology to survey the sky." The rest of the development funds came from NASA, the PS1 Science Consortium (PS1SC) and the State of Hawaii. As it exists today, the Pan-STARRS System [3] consists of the two wide field survey telescopes (PS1 and PS2) and supporting computing clusters, the Image Processing Pipeline (IPP) , the Moving Object Processing System (MOPS), the Transient Science Server (TSS), and the hierarchical database of objects and their attributes (PSPS). The images and database from the Pan-STARRS1 Surveys is available from panstarrs.stsci.edu [3]. The Pan-STARRS1 Surveys (2010-2014) were supported by the Pan-STARRS Science Consortium, NASA, and the University of Hawaii [3]. From 2014 to the present, Pan-STARRS operations are supported at the 90% level by NASA for NEO discovery and characterization. In this time Pan-STARRS has been a major contributor in the ongoing search for Near Earth Objects (NEOs), presently discovering over 40% of all new NEOs, and over 50% of the larger NEOs and Potentially Hazardous Asteroids (PHAs) [4,5]. These discoveries have been made with the Pan-STARRS1 Telescope (PS1). The Pan-STARRS2 Telescope (PS2) is currently undergoing commissioning conducting science verification observations and is expected to be fully operational shortly. (See Figure 1, the Pan-STARRS Observatories).

With the combined survey power of both PS1 and PS2, Pan-STARRS can perform a wide area survey with well-behaved selection effects and completeness over the available sky. This will provide a major contribution to NASA's NEO Observation program goal of discovering all potentially hazardous NEOs down to a size of 100 meters. We note that approximately half of the NEOs that Pan-STARRS discovers have a diameter of 100 meters or larger: the ability to discover these larger NEOs is one of the major strengths of the Pan-STARRS telescopes. The proposed baseline NEO survey has a built-in follow-up component that will increase the number of Pan-STARRS detections that are recovered within a few days of discovery. Pan-STARRS is known for its astrometric and photometric accuracy, and both will improve with the application of our latest Gaia-tied reference catalog [6]. With the factor of 2 increase in survey capability from the second telescope, and together with software improvements the full Pan-STARRS Observatory should more than double the current NEO discovery rate.

Figure 1: The Pan-STARRS Observatories, located near the summit of Haleakala on the site of what was the LURE Observatory. The PS1 and PS2 domes are precisely north-south of each other, connected by a common support building. Pan-STARRS1 or PS1 (F51) is on the right. The Pan-STARRS2 telescope, or PS2 (F52) is on the left. The optics of both systems are nearly identical. However the telescopes and domes are quite different and were built by different manufacturers. The two observatories are not completely independent — they share power, cooling, computing resources and network connectivity.

2. THE PAN-STARRS1 SYSTEM

The Pan-STARRS Telescopes have a 1.8 meter aperture at f/4.4, and use a Ritchey-Chretien design with a 3-element set of corrector lenses, one of which is the window to the cryogenic camera. Each telescope has a Bonn shutter and filter mechanism that can hold six filters: grizyw. The system has 3.2 degree diameter field of view.

2.1 The Gigapixel Camera 1

The camera on PS1 is the GigaPixel Camera1, or GPC1. The CCDs in GPC1 are Orthogonal Transfer Array (OTA) devices made by MIT Lincoln Laboratory (MITLL). GPC1 has 60 CCDs, each of which has 4800x4800 active pixels arranged in a grid of 8x8 cells, each of which has 600x600 pixels, resulting in a 1.4 gigapixels. These unusual OTA devices were intended for on-chip image motion compensation (but this was never used). Earlier implementations of OTAs did perform well in this manner, but the existing devices in GPC1 had high noise properties making them unsuitable for that technique. The complexity of the OTA devices introduced undesirable characteristics in their performance including (i) a low fill fraction from the gaps between the cells on each device (64 cells per chip), (ii) large regions of poor charge transfer that require masking and further reduce the fill factor, (iii) persistence effects in which exposures with modestly bright stars left “sticky” charge at those chip positions that would persist for many subsequent exposures, and (iv) correlated read noise. The latter two of these phenomena contribute to a large number of false positive detections and decrease the effective sensitivity by a factor of 1.25.

2.2 The Gigapixel Camera 2

The GPC2 Camera is significantly better than GPC1 in several respects. The corner devices were populated and the field of view is slightly larger, so there are 1.5 gigapixels. The static mask is much better, approaching the 94% design fill factor. There are no large regions of bad charge transfer which cause most of the masked active pixels in GPC1. Cosmetically the devices in GPC2 are much better than GPC1. Furthermore, the cross-talk and correlated read noise that add systematic noise to GPC1 images is largely absent in GPC2 due to design changes. However there are at present some connectivity problems that are temperature dependent and can lead to dropout of some devices. This issue is under study.

2.3 Preliminary performance comparison

Figure 2 shows plots of the current image quality on PS1 vs PS2 in images taken at the same time.

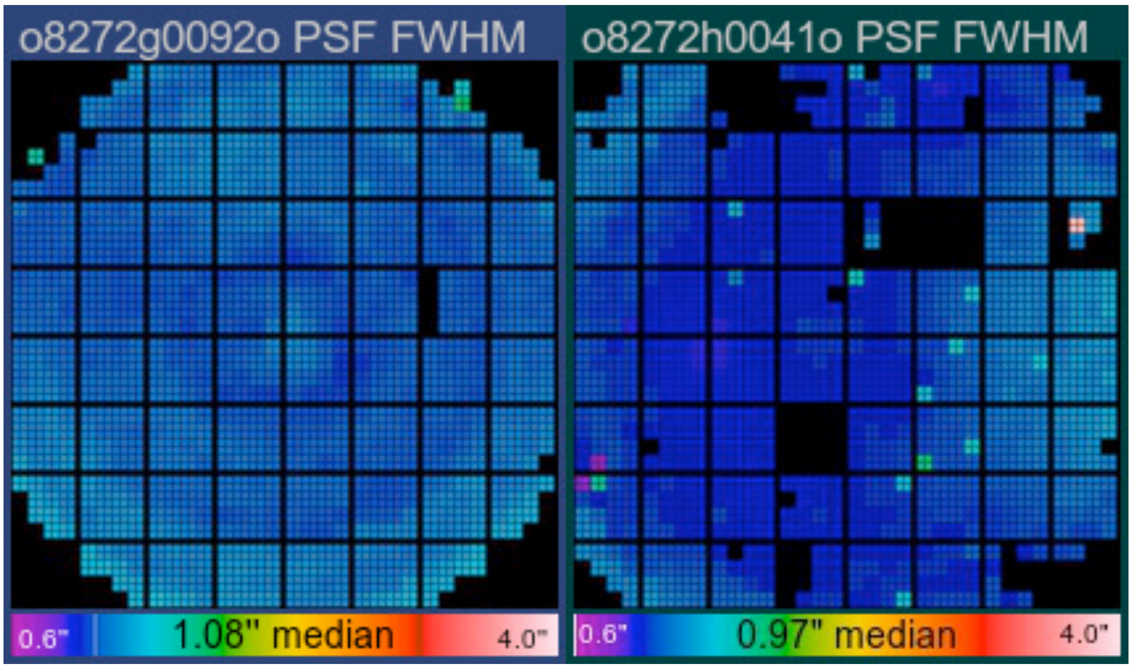

Figure 2: Left: The image quality across the field of view of the GPC1 camera on PS1. Each superpixel is color coded to the FWHM of the PSF. The ring structure and particularly the peak in the center are due to fabrication imperfections in the corrector optics. Right: The image quality on with GPC2 on PS2 at about the same time. The image quality as measured by the FWHM of the PSF is much smoother, demonstrating the superior fabrication of the PS2 optics. The dropouts are due to thermally sensitive connections and mitigation is under study.

3. PAN-STARRS DISCOVERIES

Pan-STARRS1 has made a great many discoveries [3], Figure 3 gives a summary of the time domain discoveries since the end of the Pan-STARRS Science Consortium. These include the discovery of the first interstellar object ever discovered, 'Omuamua [6] and important photometry of the kilonova associated with the first binary neutron star merger discovered by LIGO [7,8].

PS1 Discoveries:2014-2017

Near Earth Objects	3835
Potentially Hazardous Asteroids	299
Comets	171
Trans-Neptunian Objects	323
Supernova reported to IAU (since Jan 1, 2016)	7398

~ 2 NEOs / night
~ 11 Supernova / night (transients)

First Interstellar Object - `Oumuamua

Transient Surveys	No. of Supernova Since 2016
Pan-STARRS1	7398
Gaia Alerts	3274
ATLAS	1175
ASASSN	360
iPTF	127

NEO Surveys	No. of NEOs
Pan-STARRS1	3835
Catalina	3118
All other NEO surveys	504

Pan-STARRS1 reports more discoveries of Solar System Objects and Supernova than all other current surveys combined.
PS2 should ~ double the discovery rate.

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Figure 3: Tables of Pan-STARRS discoveries and comparison with other surveys.

4. THE PAN-STARRS WIDE AREA SURVEY FOR NEOS

With the addition of PS2, the combined survey power of both Pan-STARRS telescopes allows for a new survey strategy. There are many ways to try to optimize the survey strategy in order to maximize the NEO discovery rate, and simulations have been produced by Lilly et al. (2016). In practice, our strategy will evolve as we gain experience using PS1 and PS2 in tandem, together with more sophisticated simulations. Here we discuss one simple strategy where PS1 and PS2 we can do meridian stripe quads from (–49º < Dec < +90º) in a night. In Figure 3 the results of a three year simulation with this strategy are shown. The survey is done in w-band in dark time for the greatest sensitivity, i-band in grey time, and z-band at bright time and in twilight.

The survey is done in w-band in dark time for the greatest sensitivity, i-band in grey time, and z-band at bright time and in twilight. The NEO wide area survey discovers not only NEOS, but other solar system objects (Comets, asteroids, Kuiper Belt Objects) but many supernova and other astronomical transients as well. These are all posted to the IAU Transient Server and many are followed up spectroscopically and photometrically.

5. THE UNIONS SURVEY

The combination or stack of the Pan-STARRS NEO Survey observations will provide deep images over the northern extragalactic sky in the w, i, and z bands. These are complimentary to the Canada France Imaging Survey in u-band and r-band in progress with the Megacam instrument on CFHT on Mauna Kea. The two teams have formed an alliance to combine there data into the Ultraviolet Near Infrared Optical Northern Survey or UNIONS. This combination will provide a 4 band northern extragalactic sky survey that will be deeper than the Dark Energy Survey in the southern hemisphere and approximately as deep as the first year of LSST observations.

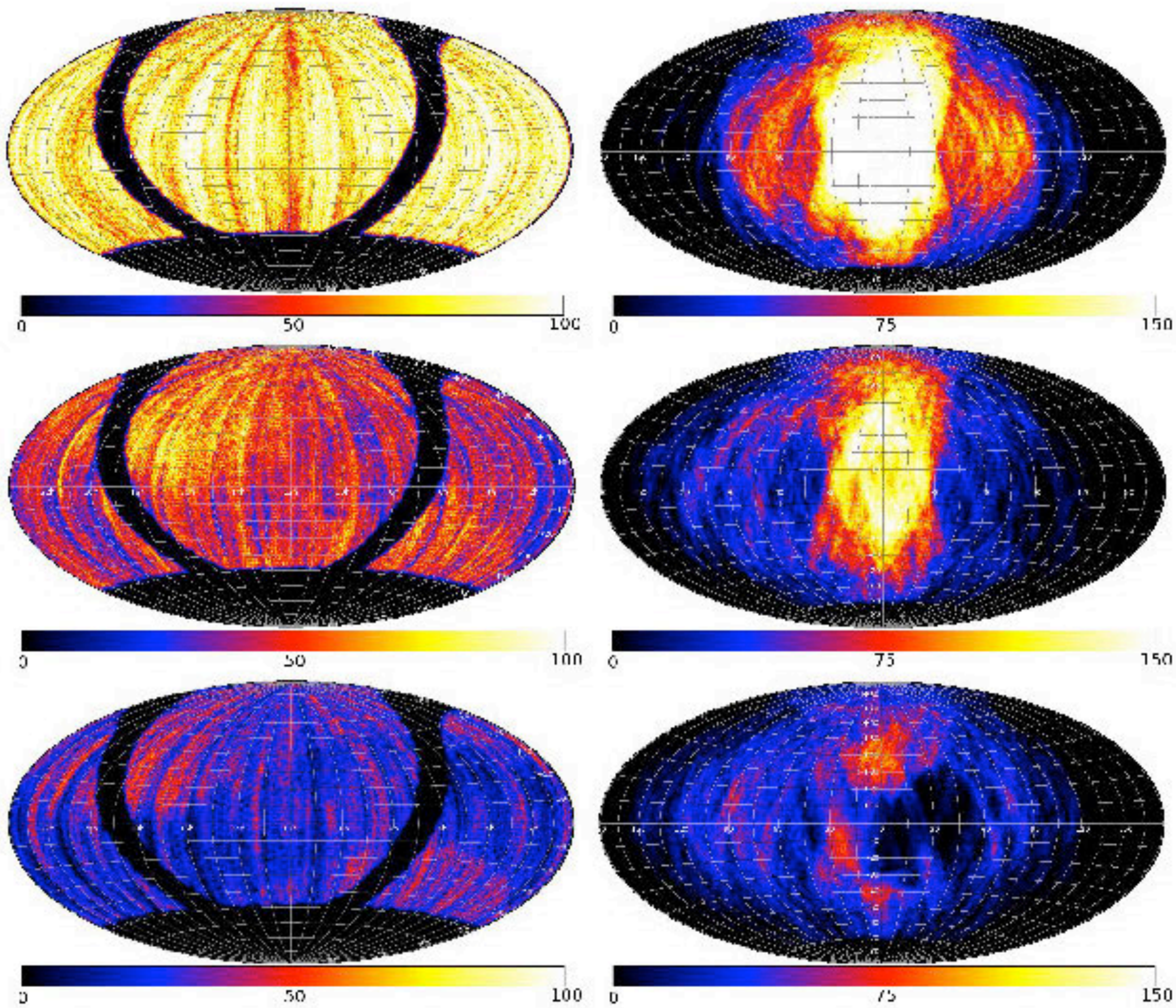

Figure 3:Left column: the simulated sky distribution of observations by PS1 & PS2 for a three year period. The value is the number of exposures. The back band is the galactic plane which is excluded because of the difficulty of finding objects where the star density is high. Bands are w, i, and z band from top to bottom. Right column: distribution of observations with respect to opposition from simulated survey (x - axis: distance from opposition, y-axis: ecliptic latitude) in w, i, and z band.

The UNIONS survey, hopefully complemented by a g-band survey, will provide the deepest northern sky survey for the foreseeable future. As such it will provide the photometric redshifts for the EUCLID space mission. EUCLID will provide single epoch deep high resolution images of the extragalactic sky to detected weak lensing, and the combined data set will allow for the tomography of the dark matter in the universe [9].

6. REFERENCES

1. Kaiser N., Aussel H., Burke B., et al. 2002, in Proc. SPIE, Vol. 4836, 154-184
2. Kaiser N., Burgett W., Chambers K., et al. 2010, in Proc. SPIE, Vol. 7733, 77330E
3. Chambers K.C., Magnier E.A., Metcalfe N., et al. 2016, arXiv:1612.05560
4. Wainscoat R.J., 2016, IEEE Aerospace Conference, 7500568
5. Wainscoat R.J., Chambers K., Lilly E., WerykJohnson, N.L. and McKnight, D.S., *Artificial Space Debris*, Orbit Book Company, Malabar, Florida, 1991.
7. Abbott et al. 2017, ApJ 848, 12
8. Meech et al., 2017, Nature 552, 378
9. Euclid Consortium, ESA, SRE 2011