SPACEWATCH SUPPORT OF DEEP WIDE-FIELD NEO SURVEYS

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1. SUMMARY

Abstract

The Spacewatch Project[1] (McMillan *et al.* 2007) uses ground-based optical telescopes to detect Near-Earth Objects (NEOs) to faint limiting magnitudes, and specializes in following up NEOs as they recede from Earth and get fainter after discovery. Followup tracking is needed to consolidate knowledge of the orbits of NEOs during their discovery apparitions because return apparitions can be several years away, and survey programs can not always revisit their own discoveries. Spacewatch is being groomed for quick response to the needs of upcoming missions that will discover NEOs in unprecedented numbers. Potential improvements range from relatively inexpensive upgrades of electronics and software to more ambitious new detectors, new optics, and use of larger telescopes. Telescopes available to Spacewatch on Kitt Peak mountain in Arizona range from 0.9-meter to 4-meters in diameter, capable of recovering 140-meter diameter NEOs as far away as an Astronomical Unit. Formal agreements between Spacewatch and the Wide-field Infrared Survey Explorer (WISE) mission and between Spacewatch and the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) attest to those projects' needs for Spacewatch services.

Introduction

The Spacewatch Project detects NEOs to fainter limiting magnitudes than most other stations. Spacewatch equipment, developed over many years, is best suited nowadays to followup, recovery, and prediscovery observations of NEOs. These services are needed to complete the inventory of 90 per cent of the NEOs with diameters of 1 km and larger and extend knowledge of smaller objects. The Spacewatch 0.9-meter and 1.8-meter telescopes lead the world in

1 http://spacewatch.lpl.arizona.edu

followup observations of Potentially Hazardous Asteroids (PHAs) with diameters larger than 140 meters while they are fainter than V magnitude 21.5. Thus Spacewatch follows up NEOs at relatively large distances from Earth, thereby improving knowledge of their orbits. Approximately 3,000 detections of NEOs, where one “detection” = 3 observations of position, are made by Spacewatch per year. About ¼ of the objects observed are PHAs. Spacewatch intends to follow the discoveries of the WISE mission in 2010 (Mainzer *et al.* 2005) as well as Pan-STARRS-1 (PS1; Jedicke *et al.* 2007), which will fully utilize the magnitude sensitivity of Spacewatch.

The Case for More Followup Observations

Asteroids tend to be discovered at their brightest and most geometrically favorable appearances, so it is inevitable that they tend to become more difficult to detect in the days and weeks following their discoveries. It is also inevitable that most discoveries of asteroids are made near the limit of detection of the surveys that discover them, due to fields of view sampling larger volumes of space at greater distances. It follows that surveys that push their detections of asteroids to the limit of sensitivity cannot be expected to make enough followup observations during the normal course of their surveys, even if they revisit the same areas of the sky every few days. Recently discovered faint asteroids tend to drop below the limit of detection before enough observations spanning a long enough arc can be collected by repeating search patterns. On the other hand, targeting followup observations on individual objects allows detection to dimmer limits and more prolonged tracking of asteroids’ paths. Furthermore, a survey that attempts to follow up all its discoveries by targeting specific objects with longer exposures would quickly become saturated with followup duty at the expense of its search pattern for new objects. Therefore, separate telescopes dedicated to followup and able to reach dim objects have been essential to the campaign.

The NEO search community has been fortunate to be supported by a world-wide cohort of volunteers who follow up many of the brighter asteroids, leaving the larger professional followup telescopes free to concentrate on the dimmer targets. But despite all the dedicated observers and self-followup by surveys, some important NEOs have slipped away before sufficient observations are made during their discovery apparitions.

In each lunation of observing, Pan-STARRS will detect several times as many solar system objects as are currently known (Jedicke *et al.* 2007). The Large Synoptic Survey Telescope (LSST; Ivezić *et al.* 2007) will be able to do even better than that later. These surveys will self-follow most of their own discoveries by repeating their search patterns, but even if only a few percent of the detected NEOs need additional followup, the total number of followup targets will be much greater than today. *Nor would it be acceptable to allow that small percentage of unlinked NEOs slip away, because they may tend to be the ones with the more unusual orbital elements.* So if anything, expansion of surveys to larger areas of sky and fainter magnitudes will demand more targeted followup observations rather than less.

Some statistics and examples illustrate the shortage of followup observations, even among important NEOs. On 2009 Feb 20 the MPC listed 1022 PHAs: asteroids with absolute magnitudes H brighter than or equal to 22 and Mean Orbital Intersection Distances (MOIDs) with the Earth's orbit $\leq$0.05 AU. Some 395 such objects were not observed after their discovery apparitions. Of those, 175 objects had observational arcs spanning less than 30 days (not counting 10 objects discovered less than 30 days prior to the summary date of Feb 20). Seven of those 175 objects have arcs < 3 days and three of the 175 short-arc objects are "big" (H$\leq$18.5; diameters $\geq$ 800 $\pm$400 meters).

However, the MPC's definition of "PHA" does not take into account whether the object and the Earth appear at the same time near the point where the orbits are close. So we should look at lists of closely-approaching objects to see how well those even more important NEOs are followed up. As of 2009 Feb 23, the MPC listed 927 potential close encounters with Earth by NEOs between the years 2009 and 2178, 187 of which encounters were predicted to be by objects observed during only their discovery apparitions. Even diligent followup during a discovery apparition is not always sufficient for recovery. PHA 2003 BK47 was discovered by Spacewatch at V=21.8 and pounded with 50 observations spanning more than a month, yet the uncertainty of its ephemeris at its next favorable apparition in 2011 will be 2-3 degrees.

Lists of potential impactors also call for better followup. On 2009 Feb 17, JPL listed 28 NEOs with H$\leq$22 (diameters 75-240 m) that might have future close encounters with Earth. Nine of those are considered lost, and two of those, 2001 CA21 and 1979 XB, are "big" as defined above. Five of the nine lost objects were discovered within the last 3 years by modern surveys. 1979 XB, discovered photographically, has a diameter between 370 and 1200 m and has only a 4-day arc of observations ending on 1979 Dec 15. On 2009 Feb 17 it was listed on both the JPL and NEODyS web sites with finite risk of impact, yet has not been rediscovered in 29 years despite the new surveys and a synodic period supposedly of only 1.4 years. Its current 3-sigma ephemeris uncertainty is 37 degrees. Rediscovery may be handicapped by its aphelion distance of 3.8 AU, "hiding" the object in and beyond the main asteroid belt much of the time.

One final notable example is (719) Albert, discovered visually through an eyepiece in 1911. It is a "big" Amor asteroid with a diameter ~2 km. However, it was lost because favorable apparitions occur only every 30 years despite a synodic period of only 1.3 years. It was missed in 1941 due to understandable inattention, missed in 1971 due to the large uncertainty, and only in 2000 finally rediscovered by Spacewatch (Larsen *et al.* 2000). Immediate and extensive followup can prevent important objects from being lost for a long time.

Requirements for Better Followup

A prescription for enhancements to the global followup capability is beyond the scope of this paper, but the requirements are described by four parameters: limiting magnitude, area coverage, response time, and number of targets observed per unit time. Sky conditions can allow V=23rd magnitude to be reached at most sites, and that corresponds to the requirements for followup of both WISE and Pan-STARRS-1 targets. The expected demands of WISE on area coverage are described below. Response time must be well within the duration of an apparition, preferably 1-3 days for newly discovered objects and several days in the cases of recoveries of asteroids returning on a subsequent apparition. Efficient followup at V=23 is about 3 targets per hour per telescope. A deeper limiting magnitude, in our experience, is more important to followup than wider area coverage because the uncertainty maps of most followup targets can be covered by a few exposures with existing equipment.

Spacewatch Effectiveness: Spacewatch is responsible for about a third of all observations of PHAs fainter than or equal to V=20.5, and an even larger fraction for V≥21.5, making it the most productive PHA followup effort (Figure 1). Spacewatch followup also fills an important niche in the time domain. Figure 2 illustrates how Spacewatch dominates the effort to extend knowledge of orbital arcs of PHAs while they are faint, and Figure 3 shows how we have improved our rate of detection of PHAs with time. Spacewatch also follows up any accessible NEOs listed by JPL or NEODyS with potential impact solutions, without regard to absolute magnitude. Since 2002 January 1 when JPL's virtual impactor list was begun, Spacewatch observations have contributed to the removal of about half of the many hundreds of such objects removed from that list.

Assistance to Pan-STARRS: The next year will see the beginning of the operation of the Pan-STARRS prototype PS1 of the University of Hawaii's Institute for Astronomy (Kaiser *et al.* 2005; Jedicke *et al.* 2005a, b; 2007, 2008). A formal Memorandum of Understanding between Spacewatch and Pan-STARRS was signed by the administrations of both universities in 2008. Spacewatch provided PS with lists of detected point sources on which they tested their linking software. Spacewatch transient data were the first real data to be processed by PS and they were invaluable in establishing their operational capabilities under realistic inputs.

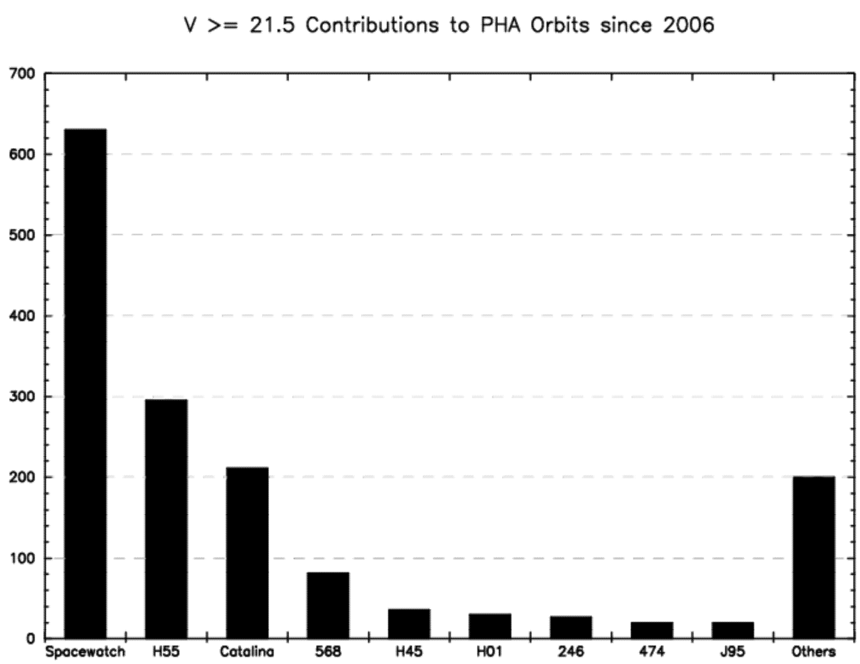

Figure 1. Observations (lines of astrometry) of PHAs with ephemeris magnitudes V≥21.5 from

2006 Jan. 1 to 2009 Feb. 11, by observing station. "Spacewatch" = Station codes 691+291. "Catalina" = stations G96+703+E12+413+693. "H55" = R. Holmes/ARO, Charleston, IL.

PS1's revisits of areas surveyed during a lunation will allow them to determine preliminary orbits of asteroids spanning 4-8 days. However, additional followup observations with other telescopes would help PS1 make linkages in their archives and avoid losing objects. Jedicke (2006 private communication) estimated that PS1 will detect thousands of NEOs with H≤22. If there are ~50,000 NEOs with H≤22 (Stuart 2001), PS1 may detect ~5,000 NEOs to its limiting V magnitude of about 22.5 during its operational lifetime. About 10% of those might lack a third night due to weather, picket fence, and other incompleteness effects (e.g. camera fill factor, guiding OTA cells), and another ~10% might have poorly determined orbits. Jedicke further emphasizes that PS1 has *no* intention to do targeted followup of *any* target, only regular surveying of what happens to reappear in survey fields. So PS1 may need followup at the rate of ~200-300 NEOs per year. About 2/3rds of those should be accessible to Spacewatch with our limiting magnitude, weather and declination constraints. With ~1000 hours of clear observing time per year with 2 telescopes, and a current annual average of ~3000 detections of NEOs per year, Spacewatch should be able to target and follow up ~200 extra NEOs per year at least once. Absorbing this burden into the existing target list is feasible because some of the targets Spacewatch currently follows are lower-priority non-hazardous NEOs, and the brighter (V≤21.5) PS1 targets can be absorbed into the survey pattern covered by the automated 0.9-m telescope.

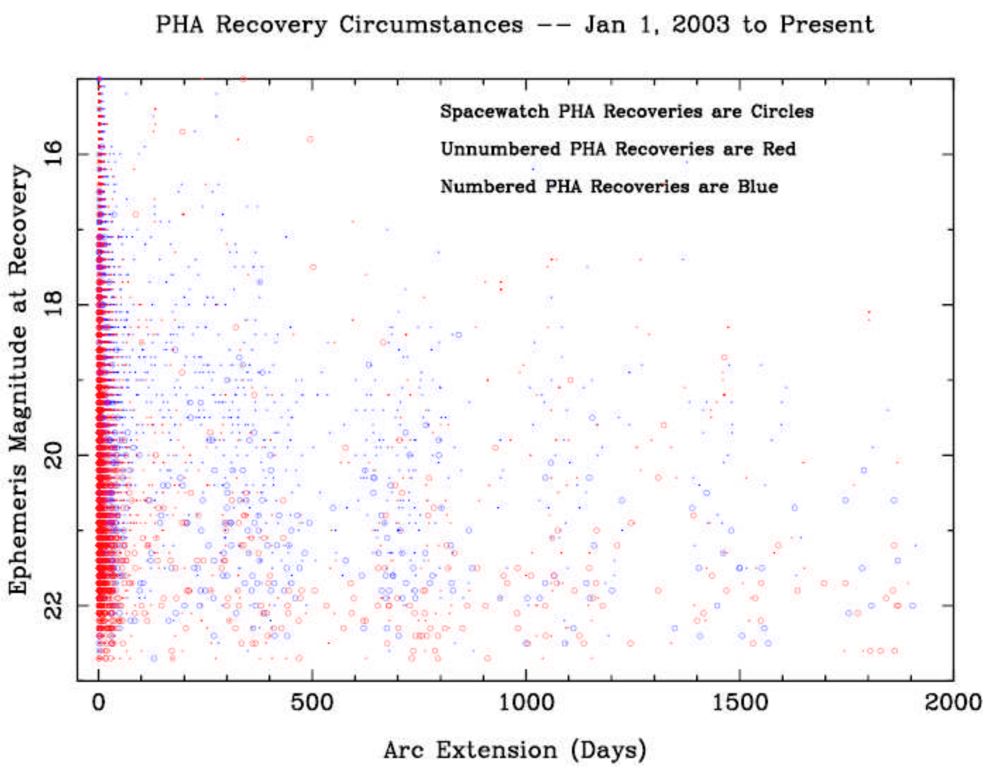

Figure 2: Apparent V magnitude versus orbital arc extension in days for all PHA observations, 2003 to the present. Spacewatch recoveries are circles and recoveries by other stations are small dots (The reader may have to magnify the display to see the dots.) Note Spacewatch

disproportionately contributes to long arc observations compared to other recovery groups. Additionally, Spacewatch contributes the bulk of the faint followup for long arcs.

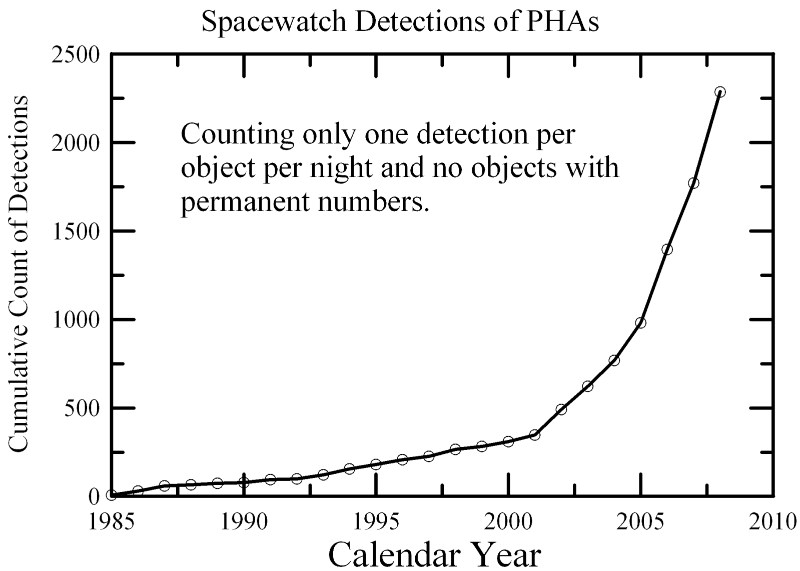

Figure 3. Detections of PHAs by Spacewatch vs. calendar year, showing our improvement in capability and output with time. Multiple detections of the same object on one night are not counted, nor are detections of "numbered" PHAs whose orbits are already well known.

Support of the WISE mission: E. L. Wright of UCLA is the Principal Investigator of the WISE mission (Mainzer *et al.* 2005). McMillan is a co-investigator. WISE is scheduled to launch in November 2009. It will map the whole sky at thermal infrared wavelengths with hundreds of times better sensitivity than the very successful IRAS mission of the 1980s, and will detect hundreds of NEOs, as well as hundreds of thousands of asteroids in the main belt. The WISE team selected Spacewatch in 2001 as their ground-based collaborator because the NEOs that WISE expects to discover will run as faint as V≈21. Because WISE will scan great circles ~90° from the Sun, some of the NEOs it will detect may have eluded ground-based surveys. This elongation also happens to be near where Earth impactors tend to dwell the longest (Chesley and Spahr 2004). Spacewatch has demonstrated the capabilities to survey and follow up at solar elongations as small as 55 degrees and as faint as V≈23 (McMillan *et al.* 2007). Typical WISE detection tracklets will have at least 8 and usually 12 or more positions at 3 hour intervals spanning ~30-36 hours. This is unusually good temporal coverage for a discovery,

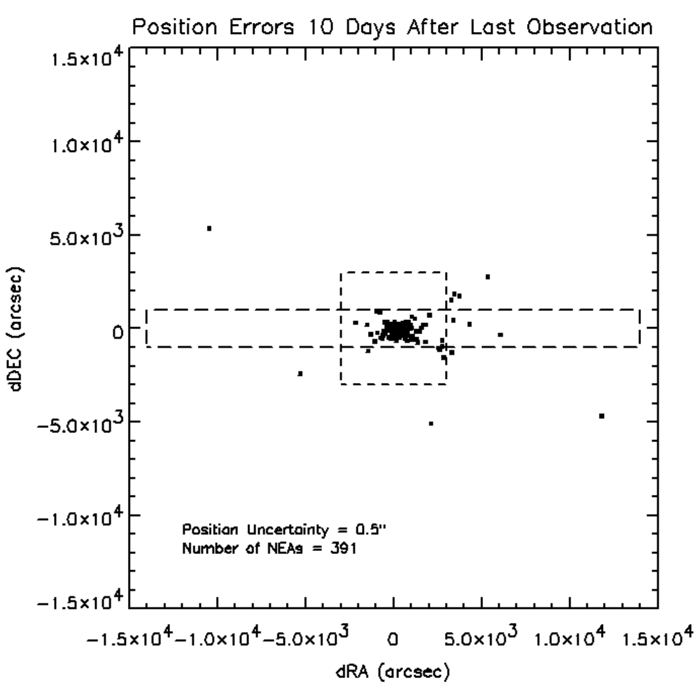

Figure 4. Scatter of extrapolated positions of NEOs from true positions after simulated detection by WISE 10 days earlier, compared with fields of view/scan of Spacewatch 0.9-m/1.8-m telescopes (Walker and Kiefer 2006).

compared to the tens-of-minutes-long discovery arcs by ground-based observatories, so discrimination of orbital class and ground-based recovery will be easier than it usually is at this elongation. WISE is requesting funds to process and distribute its detections of moving objects "soon" enough (days) so the objects can be recovered with ground-based telescopes after searching only a few square degrees of sky. The feasibility is illustrated by Figures 4 and 5.

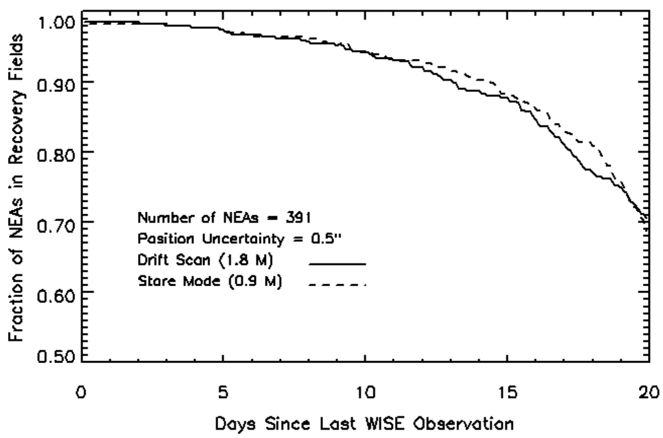

Figure 5. Predicted fraction of NEOs to be detected by WISE contained in Spacewatch fields of view, versus days since simulated WISE observation (Walker and Kiefer 2006).

Proposed Enhancements to Spacewatch:

Upgrades to the 1.8-meter Telescope:

Considering that the Spacewatch 1.8-meter telescope still seems to be the largest telescope dedicated full time to astrometry of solar system objects, it is logical to enhance its sensitivity. Under good conditions this telescope has reached the 23rd V magnitude in recovering asteroids. Relatively modest enhancements will make that limit a more routine application. This will double the number of faint (V>22.5) asteroids accessible to this telescope.

Improvements to software at modest cost will increase the number of objects observable per night by 20-50%. Target selection, telescope pointing, focusing, rotation alignment are close to becoming automatic with an additional layer of software to control the individual processes. Better adaptation of search patterns with the uncertainty maps of targets is possible on both Spacewatch telescopes.

New detectors on the 1.8-meter telescope are long overdue. The CCD we use is of early 1990s vintage with high quantum efficiency but very slow readout. Faster readout will allow us to take "staring" exposures, rather than drift scanning at the sidereal rate, giving us more flexibility in exposure times and more efficient search patterns. Also, due to a procedure in manufacturing, the CCDs made by that company were not flat. We have compensated for the spherical component of the CCD shape by means of the prescription of the coma corrector lenses, but it is still not possible to get good focus over the whole CCD at once. We already have two modern CCDs of larger area than the present one, so with funds to develop the housing, electronics, and cooling system, we estimate we can gain 0.5 magnitude in sensitivity and tens of percent in time efficiency.

Use of Larger Telescopes: Furthermore, we propose to make use of the "Target of Opportunity" (ToO) option for competitively awarded time on the 4-meter telescope of the Kitt Peak National Observatory and the 3.5-m WIYN telescope, also on Kitt Peak. Time may also be available with the 90Prime Camera (Williams *et al.* 2004) on the 2.3-m Bok Telescope of the Steward Observatory through informal arrangements with previously scheduled observers. To take advantage of these three additional telescopes we propose funds to add another staff member to the Spacewatch group; the telescope time itself does not require funding. These telescopes will allow access to asteroids as faint as V=23 even when observing conditions are not good enough to reach that magnitude with the Spacewatch 1.8-meter. We estimate that ~100 hours of ToO time could be obtained per year among these telescopes, allowing ~100-300 high priority faint asteroids to be recovered that would otherwise have to wait for other more favorable apparitions. This is a significant fraction of the targets we expect to receive from the WISE and Pan-STARRS-1 Projects. An additional full time staff member is expected to be needed because although the number of observing hours may be small, the observer would have to become familiar with the other equipment and software, propose and organize the observations, reduce and report the data, and be available on-site when necessary to make the observations. Physical studies of the targeted asteroids would also be possible with that equipment.

2. PRELIMINARY COST ESTIMATES

Options for funding at 3 levels:

1 Full Time Equivalent (FTE) person ≈ $130K. Personnel costs include employee-related expenses and all costs except equipment include indirect costs (overhead burden).

A. Continued operations at subsistence level with no upgrades:
   Annual Expenses:
   1.00 FTE Faculty + 3.00 FTE Science & technical support
   + $67K/yr operations, travel, materials, supplies, etc.

B. Continued operations with modest upgrades & expansion to larger telescopes:
   Annual Expenses:
   1.00 FTE Faculty +4.00 FTE Sci/tech support
   + $80K/yr operations, travel, materials, supplies, etc.

C. All of the above plus new pair of detectors on 1.8-meter telescope:
   Above "B" annual costs plus one-time costs:

Hardware commercially procured:
"New" detectors: N/C; already in hand.
Cryostat & cooling system: $50K
Electronic components: $10K

One-time in-house personnel costs:
Electronics, firmware, mechanical: 9 person-months FTE.
Software modifications & enhancements: 3 person-months FTE.

3. ADVANTAGES AND DISADVANTAGES

The advantages of Spacewatch are:

- Better orbits for many discovered NEOs, especially PHAs.
- Avoidance of loss of some objects after discovery.
- Prompt response to urgent requests from MPC and JPL.
- Experienced personnel, exclusive-use dedicated operational assets, sited with excellent infrastructure and good conditions.
- Predictable costs (mostly payroll for existing personnel).

While Spacewatch is a low-risk investment, it does have limitations. Spacewatch does not observe south of about -25 degrees declination and has a lower detection efficiency below about -10 deg. Additionally, Spacewatch's limiting magnitude is probably inferior to that achievable at a darker site with better seeing, such as in Chile or Hawaii. Finally, daylight, moonlight, and weather limit efficiency compared to a spacecraft in (say) an L1 orbit. These limitations are mitigated by the lack of equivalent telescopes in the southern hemisphere doing as much targeted followup, and that any spacecraft will create a need for more ground-based followup rather than less. Spacewatch represents a major investment and should be used.

References

Chesley, S. R., and T. B. Spahr. 2004. Earth impactors: Orbital characteristics and warning times. In *Mitigation of Hazardous Asteroids and Comets,* Eds. M. Belton et al., Cambridge Press, 22-37.
Ivezić, Ž., *et al.* 2007. LSST: Comprehensive NEO detection, characterization, and orbits. In *Proc. IAU Symp. 236: Near Earth Objects, our Celestial Neighbors: Opportunity and Risk,* A. Milani, G. Valsecchi, and D. Vokrouhlicky, Eds. (Cambridge U. Press), pp. 353-362.
Jedicke, R., *et al.* 2005a. The Pan-STARRS Moving Object Processing System. *BAAS,* **37,** 637.
Jedicke, R., *et al.* 2005b. Pan-STARRS Moving Object Processing System. *BAAS* **37,** 1363.
Jedicke, R., *et al.* 2007. The next decade of Solar System discovery with Pan-STARRS. In *Proc. IAU Symp. 236: Near Earth Objects, our Celestial Neighbors: Opportunity and Risk,* A. Milani, G. Valsecchi, and D. Vokrouhlicky, Eds. (Cambridge U. Press), pp.341-352.

Jedicke, R., and the Pan-STARRS Team. 2008. Pan-STARRS: First solar system results. In Asteroids, Comets, and Meteors, held July 14-18, 2008 in Baltimore, Maryland. LPI Contribution No. 1405, paper id. 8301.

Kaiser, N., and the Pan-STARRS Team. 2005. The Pan-STARRS Survey Telescope Project. *BAAS* **37,** 1409.

Larsen, J. A.; McMillan, R. S.; Scotti, J. V.; Hicks, M.; Fevig, R.; Williams, G. V. 2000. (719) Albert = 2000 JW8. *IAU Circ.* 7420, 1. Edited by Marsden, B. G.

Mainzer, A. K., P. Eisenhardt, E. L. Wright, F-C. Liu, W. Irace, I. Heinrichsen, R. Cutri, and V. Duval. 2005. Preliminary design of the Wide-Field Infrared Survey Explorer (WISE). *UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts II.* (H. A. MacEwen, Ed.) *Proc. SPIE* **5899,** 262-273.

McMillan, R. S., and the Spacewatch Team. 2007. "Spacewatch Preparations for the Era of Deep All-sky Surveys". In *Proc. IAU Symp. 236: Near Earth Objects, our Celestial Neighbors – Opportunity and Risk,* A. Milani, G. Valsecchi, and D. Vokrouhlicky, Eds. (Cambridge U. Press), pp 329-340.

Stuart, J. S. 2001. A near-Earth asteroid population estimate from the LINEAR survey. *Science* **294,** 1691-1693.

Walker, R., and H. Kiefer. 2006. *Progress Report on a study of the required turn-around time for WISE observations of NEAs.* Internal report to WISE Science Team presented at Asilomar, CA in Nov. 2006.

Williams, G. G., E. Olszewski, M. P. Lesser, and J. H. Burge. 2004. "90prime: a prime focus imager for the Steward Observatory 90-in. telescope", In *Ground-based Instrumentation for Astronomy,* Eds. A. F. M. Moorwood and I. Masanori. *Proc. SPIE* **5492,** 787-798.

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