SYNERGISTIC NEO-DEBRIS ACTIVITIES AT UNIVERSITY OF ARIZONA

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ABSTRACT

The University of Arizona (UoA) is a world leader in the detection and characterization of near-Earth objects (NEOs). More than half of all known NEOs have been discovered by two surveys (Catalina Sky Survey or CSS and Spacewatch) based at UoA. All three known Earth impactors (2008 TC3, 2014 AA and 2018 LA) were discovered by the Catalina Sky Survey prior to impact enabling scientists to recover samples for two of them. Capitalizing on our nearly half century of leadership in NEO discovery and characterization, UoA has embarked on a comprehensive space situational awareness program to resolve the debris problem in cis-lunar space. As part of this Space Situational Awareness Arizona (SSA-Arizona) initiative we are working to leverage our NEO expertise, and to apply them towards the development of a faint debris catalog in geostationary and cis-lunar space.

1 CATALINA SKY SURVEY

The University of Arizona (UoA) has deep research and operations experience in topics related to Near Earth Objects (NEOs), that is, of asteroids and comets that approach the vicinity of Earth, presenting both a risk of impact as well as the opportunity for scientific research. The Lunar and Planetary Laboratory (LPL) of the UoA operates space-based NEO missions such as OSIRIS-REx [1], now exploring the asteroid Bennu (to culminate in returning a sample in 2020), and NEO projects on the ground, namely the Catalina Sky Survey (CSS) [2] and targeted follow-up observations by both CSS and LPL's Spacewatch [3]. CSS's four current telescopes are located in the Santa Catalina mountains of the Coronado National Forest in southern Arizona (our telescope, *E12*, located at Siding Spring Observatory in Australia, was retired in 2013). Spacewatch is based at Kitt Peak on the Tohono O'odham Nation. LPL works cooperatively with the UoA's Steward Observatory to maintain and enhance the telescopes and their varied instrumentation.

Catalina's current portfolio of telescopes includes the Mount Lemmon 60-inch (Minor Planet Center ID *G96*) for surveying, and its neighbouring 1-metre follow-up telescope (*I52*). On nearby Mount Bigelow, CSS operates the 0.7-metre Schmidt survey telescope (*703*), and its neighbour, the 61-inch Kuiper telescope (*V06*) for deep follow-up. Our survey telescopes rely on 111 megapixel 10K cameras that give G96 a 5 square-degree and 703 a 19 square-degree field of view.

Catalina Sky Survey has been a dominant contributor to the discovery of near Earth asteroids and comets over its more than two decades of operation. In 2018, CSS was the first NEO survey to discover >1000 new NEOs in a single year, including five larger than one kilometre, and more than 200 > 140 metres.

Our survey was a major contributor satisfying the international Spaceguard Goal (1992) [4] of finding 90% of the NEAs larger than 1-km in diameter, and has found more 140-m objects (2865, at current count) than any other survey toward the subsequent U.S. Congressional mandate of the George E. Brown, Jr. Near-Earth Object Survey Act (2005) [5]. Together, Catalina Sky Survey and LPL's partner NEO project, Spacewatch, have discovered more than half (Fig. 1) of the >19,000 known NEOs of all sizes.

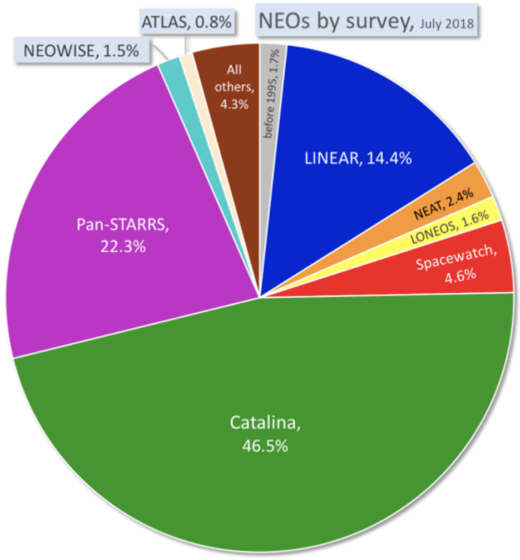

Figure 1. NEO discovery statistics by ground-based telescopes. Space-based NEOWISE survey discoveries are now shown here.

Catalina Sky Survey is the only survey to discover NEOs before they impacted the Earth. Our survey

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telescopes discovered all the three impactors, 2008 TC3, 2014 AA and 2018 LA. Tab. 1 summarizes Catalina's advantage versus its competitors in the detection and study of rapidly moving natural or artificial targets.

Survey	median °/day	mean °/day	σ	90th percentile
F51	0.35	0.9	1.3	2.1
G96	0.7	2.6	4.4	6.6
ATLAS	2.5	4.5	4.7	10.4
703	2.5	6.0	7.6	15.4

Table 1. NEOCP tracklet rates (2017) in degrees-per-day for CSS telescopes G96 and 703 versus nearest competitors, F51 and ATLAS respectively. Sensitivity to more rapid moving objects is required to observe those closest to Earth; these are preferentially smaller.

The discovery of previously unknown moving objects in the solar system, and specifically in either heliocentric or geocentric orbits near Earth, involves serendipitous surveying of large areas of the sky, combined with targeted astrometric follow-up observation. Sufficiently long arcs are required to constrain possible orbits and permit future recovery and study of diverse classes of objects. Orbital arcs are built up from multi-exposure tracklets collected from several diverse telescopes, both on the ground and in space.

Multi-threaded software systems perform pipelined point-source detections using both image differencing and catalog-based algorithms, linking observations of both types in any given tracklet. Automated moving object detection heuristics are validated by human observers in near real time to produce candidate NEO discoveries that are published within minutes to the central clearing house of the NEO Confirmation Page (NEOCP) at the Minor Planet Center (MPC) operated by the Harvard-Smithsonian Center for Astrophysics. All told, CSS has submitted more than 57 million astrometric observations to the MPC.

These have often included incidental observations of artificial objects in both geocentric and heliocentric orbits, though CSS is not tasked with targeted follow-up of such. Numerous professional and amateur third-party observatories submit follow-up observations to confirm and extend the orbits of objects of all types. CSS is a leader in technologies to optimize rapid coordinated community scheduling of observations through its NEOfixer broker, prioritizing and assigning targets to subscribing telescopes.

To complement its sensitivity to faint, rapidly moving, targets, Catalina Sky Survey is noted for its similarly rapid survey-mode and follow-up submissions and subsequent near real time response to community astrometry as compared to other projects. Low latency pipelines and observing procedures ensure that NEO candidates are confirmed in a timely fashion. It would do no good to detect a rapidly moving object and then see the observations embargoed from notifying others in the community.

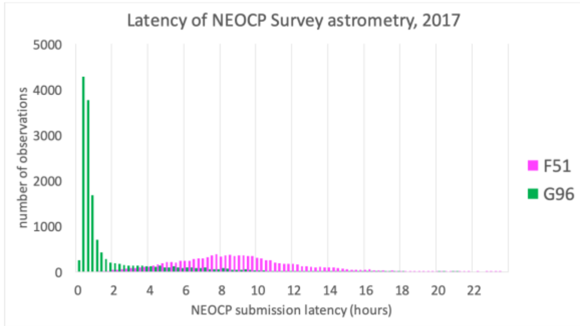

Figure 2. Comparative histograms of submissions to the NEO Confirmation Page in hours from observation to posting, for CSS 60" telescope (G96) & Pan-STARRS-1 (F51). CSS latency peaks ~half-hour; significantly less allowing for the typical 20+ minute tracklet duration.

2 SSA-ARIZONA INITIATIVE

The orbital space around the Earth is contested, congested and competitive. With over 20,000 resident space objects (RSOs) in the US Air Force catalog, the ever-increasing number of objects in near-Earth space poses a threat not only to military assets but also civilian and commercial payloads. With mega constellations being planned over the next five years, there is an increasing need to detect, track and identify RSOs so we can sustain the orbital environment for future generations. To address the new challenges afforded by the SSA domain, University of Arizona started a new initiative under the Defense and Security Research Institute (DSRI) named Space Situational Awareness Arizona (SSA-Arizona).

The SSA-Arizona Initiative is devoted to the advancement of the understanding and characterization of the behavior of man-made objects in space. The initiative pursues basic and applied research as well as development in 1) Observational techniques, methods and instruments from ground, air and space-based platforms; 2) Innovative algorithms and methods for orbit determination, space object identification, characterization and classification; and 3) Cyber infrastructures for SSA using the next generation of platforms that enables big data management and science. SSA-Arizona encompasses the previous Space Object Behavioral Science (SOBS) initiative and extends to space traffic management and space-based SSA [6]. Figure 3 shows a schematic of the general SSA-Arizona approach. The overall goal is to establish a layered and scalable approach to SSA, including a multi-layer data collection and data processing, which integrates cyber infrastructure with ground, air and space data collection platforms. Next sections will describe assets, research and development of a dedicated cyber infrastructure (named VerSSA) which may enable next generation of data sharing, big data processing and deployment of machine learning as well as ontology-based processes for knowledge discovery in the space domain.

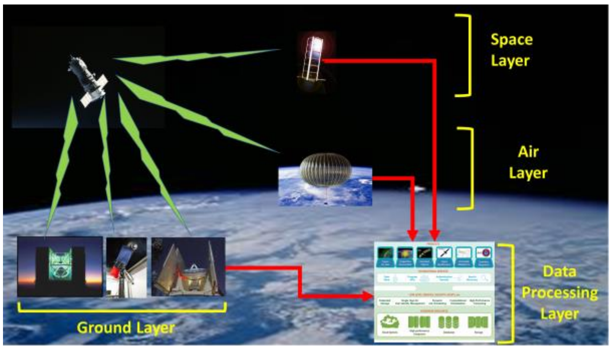

Figure 3. SSA-Arizona Initiative layered and scalable approach to SSA

2.1 Observational Assets

The UoA is the world leader in observational astronomy. In addition to the Catalina Sky Survey, SSA-Arizona personnel have been developing and deploying innovative classes of smaller telescopes specifically devoted to SSA. As an example, a new class of dedicated telescopes named Robotic Automated Pointing Telescopes for Optical Reflectance Spectroscopy (RAPTORS) has been developed and operated for characterization of RSOs [7]. RAPTORS is an automated 0.6meter F/4 telescope with transmission grating to conduct a slit-less spectroscopic survey of the GEO belt in visible wavelengths (Fig. 4). Five engineering undergraduate students constructed the telescope as part of their senior design project at the University of Arizona.

The telescope instrument combination enables us to collect visible wavelength spectra (0.4-0.8 microns) at a spectral resolution of ~30. Here, the goal is to conduct a systematic survey of the GEO belt to create a taxonomic classification of resident space objects (RSOs). As another example, the Steward Observatory SSA team developed the Pomenis Astrograph System as an alternative to more traditional narrow field of view small SSA systems. The astrograph is innovative with its fast optical design versus a traditional longer focal length found on commercial Cassegrain telescope that most “Raven class” systems are based on [8].

Figure 4. RAPTORS telescope for spectroscopic survey of GEO Belt.

3 VER-SSA

In 2018, UA signed a funded Cooperative Agreement (CA) with Air Force Research Laboratory (AFRL) to lead and develop a dedicated academic SSA collaborative research infrastructure named VerSSA with critical data management and exploitation capabilities. Establishing such a foundation supports the future vitality of SSA capabilities in the United States by providing: 1) a combined, substantive data set available to a wide variety of SSA community; and 2) support of advanced data management and exploitation tools to accelerate SSA research and application. The above mentioned SSA collaborative research infrastructure will incorporate modular development and will be founded on: 1) big data science and analytics; 2) Bayesian/probabilistic ontological frameworks; 3) object/activity based production and intelligence; 4) hard/soft information fusion; 5) semantic reasoning; and 6) machine/deep learning.

VerSSA is a scalable and cohesive computational and data management platform that brings together contemporary Data Science capabilities and supporting cyber Infrastructure for SSA. VerSSA (Fig. 5) provides flexible capabilities for securely sharing data assets and novel analysis methods among collaborating communities and individuals. VerSSA comprises a publicly accessible platform that extends National Science Foundation (NSF) CyVerse. Importantly, a restricted access version (VerSSA-R) has also been developed.

VerSSA cyber infrastructure includes: 1) A scalable secure data sharing facility (Data Store), 2) An interactive, web-based, analytical platform (Discovery Environment); 3) Cloud infrastructure to use remote servers for computation, analysis, and storage; 4) Web authentication and security services (Secure Auth and tokens); 5) Support for scaling computational algorithms to run on large, high-speed computers; 6) Education and training in how to effectively use cyber infrastructure; 7) People with expertise in all of the above to collaborate and develop novel solutions; 8) VerSSA-R, a restricted access version of public VerSSA.

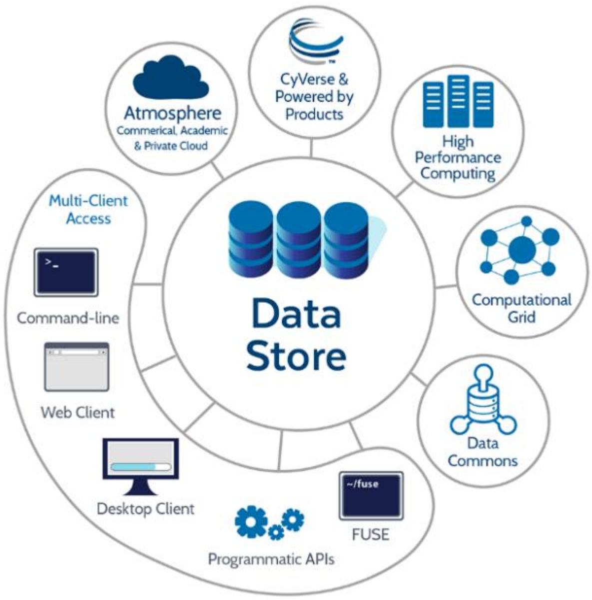

Figure 5. Schematic showing overview of VerSSA.

Under the AFRL CA umbrella, VerSSA is developed and tested to support a set of use cases to demonstrate and evaluate the desired system functionalities. High-level capabilities (functional requirements) include: 1) Data and metadata system for storage and retrieval, 2) Data acquisition via external interfaces (e.g. data from sensor networks, space weather, S/C telemetry, web), 3) Low-level data processing (e.g. astrometry pipelines), 4) High-level data processing (e.g. OD algorithms), 5) Automation of data processing (e.g. rule-based sequential processing of algorithms); and 6) User alert (e.g. email notification). The system uses Integrated Rule-Oriented Data System (iRODS) tools to efficiently upload data. Once data uploaded, meta-data is applied and analysis can start. Importantly, all available meta-data is searchable, e.g. NORAD ID, telescope, collection date, etc. Uploaded data can be selectively shared with collaborators or only visible to the uploader. Any data from any sensor can be uploaded to VerSSA, but standardization speeds analysis and improves discoverability. As such, we have developed a specific naming convention for FITS files and a directory structure in the database that automatically determine folder and telescope names based on the organization that uploads the data. Currently, we have developed an interface with RAPTORS telescope to process data for automatic astrometry and photometry data processing. Data are automatically collected, transferred and stored to VerSSA, and processed for astrometry and photometry on a nightly basis without human intervention.

Our team is conducting research in broader field of SSA, focused on innovative methods for space object identification, characterization and behavioral understanding. Methods are drawn from the field of astrodynamics, remote sensing, and machine learning, just to mention a few. As an example, we have been recently designed and trained deep Convolutional Neural Networks to classify resident space objects based on light-curve measurements [9, 10]. Additional research projects may include SSA sensor tasking for GEO catalog maintenance via deep reinforcement learning [11], maneuver detection via inverse reinforcement learning [12], development of space ontologies [6], orbit characterization via extreme learning machines [13], space object behavior characterization via Bayesian ontologies [14], Attitude and orbit propagation modeling via recurrent neural networks [15] and analysis of the placement of mega constellation for space traffic management [16] .

4 DEBRIS TRACKING ACTIVITIES

Data from the Catalina Sky Survey is useful for diverse science purposes, not just NEOs, and indeed CSS has partnered more than once with external institutions to take advantage of these opportunities. The Catalina Real-Time Transient Survey (CRTS) was a long-term collaboration with the Caltech Center for Advanced Computing Research to mine the CSS images for optical transient phenomena. CRTS discovered ~17,000 optical transients, including more than 4,000 supernovae and thousands more of diverse types from AGNs to CVs. With Steward Observatory we are currently ramping up to do a rapid follow-up search for optical counterpart events from the Laser Interferometer Gravitational-Wave Observatory (LIGO). In each of these cases, near real-time access has been arranged to the pipeline-reduced CSS data products, including imaging and the corresponding point-source catalogues.

CSS is working with the Small Bodies Node of NASA's Planetary Data System to implement public access to all our data holdings for future such efforts, but also in support of archival precovery observations, of potential interest for artificial objects as well as NEOs.

As a first step towards synergistic activities between our NEO and SSA entities at UoA, we conducted initial on-sky tests toward the SSA-Arizona initiative took place on July 1, 2018. Imaging data were acquired with two different pixel binning factors likely to span the sweet spot minimizing trailing losses for artificial geocentric rapid movers. This resulted in the visual validation of 79 objects in 15 fields binned 2x2 and a dozen candidates in half-dozen fields binned 3x3. Further analysis is ongoing.

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