# The Enhanced Catalina Sky Survey for Near-Earth Objects

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The Catalina Sky Survey (CSS) is a NASA-funded survey fully dedicated to NEO discovery. CSS operates three telescopes on Mt. Lemmon, Arizona, in support of NASA's effort to detect and catalog near-Earth objects (NEOs). In 2016 CSS deployed new large-format cameras on both the 1.5-meter and 0.7-meter Schmidt survey telescopes, increasing the nightly sky coverage by factors of 4 and 2.4 respectively. Astrometric follow-up and occasional characterization observations of NEOs are remotely performed with a refurbished 1-meter telescope, scheduled with a custom adaptive queue manager. Here we present a brief overview of survey operations, including recent modifications to our NEO search strategies enabled by the enhanced capabilities of the new cameras. Results from the first partial year of operating the new cameras are presented. We also discuss the effort to reprocess the CSS archival holdings with an improved pipeline, to measure and report an estimated 50 million asteroid and comet positions to the Minor Planet Center, and to serve the data to the public through NASA's Planetary Data System (PDS).

## Upgraded CSS Facilities

In 2016, the long-serving 4K x 4K cameras were retired from both CSS survey telescopes after over a decade of service. They were replaced with state-of-the-art Spectral Instruments cameras built around 10K x 10K STA-1600 detectors. The camera for the 1.5-m telescope, commissioned during the fall of 2016, features additional optical modifications that further enlarged the field of view to 5.0 deg$^2$. The 10K camera for the Schmidt was installed in December 2017, increasing its field of view to 19.4 deg$^2$.

| Telescope | MPC Code | f/ratio | Instrument | Field of view | Mode | Pixel scale "/pixel | 50% limiting mag. | Coverage / 10 hr. |
|---|---|---|---|---|---|---|---|---|
| 0.7-m Schmidt | 703 | f/1.8 | 10K x 10K prime focus | 19.4 deg$^2$ | survey | 0.8" | V~19.5 | 4,000 deg$^2$ |
| 1.5-m reflector | G96 | f/1.6 | 10K x 10K prime focus | 5.0 deg$^2$ | survey | 1.5" | V~21.3 | 1,000 deg$^2$ |
| 1.0-m reflector | I52 | f/2.6 | 2K x 2K Cassegrain | 0.3 deg$^2$ | follow-up | 1.0" | V~21.5 | 50-80 NEOs |

*Characteristics of current CSS survey and follow-up telescopes*

The upgrade to the Schmidt telescope also included the addition of a modern Telescope Control System, identical to the one used on the 1.5-m and 1.0-m CSS telescopes. The new *TCS-ng* features high-bandwidth network communication that allows tighter coordination between the telescope and camera that minimize the communication overheads during high-cadence survey observations. The combination of the TCS upgrade and faster camera readout increased the imaging throughput at the Schmidt by approximately 15%.

GPS / GLONASS clocks were deployed at both mountain sites and on campus, providing high precision IRIG time capture and Stratum-0 NTP time servers to the telescopes. Pulses from the shutters are captured and time-stamped, allowing calibration of the shutter open and close times to < 3 ms.

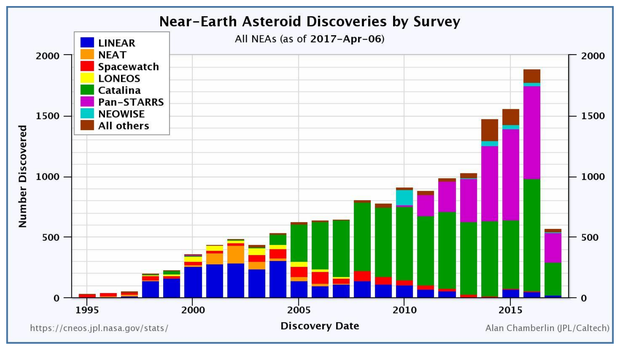
In addition to the major instrumentation upgrades, a host of infrastructure upgrades have been effected at both mountain sites and the CSS headquarters on the University of Arizona campus. The bandwidth of the radio link from the campus to Mt. Lemmon has been upgraded from 75 to 130 Mbps, while the LANs at all sites have been upgraded to 1-10 Gbps. Additional office and laboratory space has also been allocated, including a climate-controlled server room for the growing CSS archive and data processing cluster. Redundant copies of the archival data have been deployed to a data center on campus under the 24/7 oversight of the University Information Technology Services.

## New Survey Strategies

The significant increase in the survey cameras' fields of view has led to new survey strategies. Before its upgrade, the 1.5-m telescope prioritized observations near opposition and +/- 10 degrees from the ecliptic. The fourfold increase in field of view offered by the new camera has allowed the survey to expand into areas well off the ecliptic. The 1.5-m now surveys most of the visible sky from Declination -25 to +60, at solar elongations greater than about 80 degrees, about once per lunation. Survey fields have been consolidated into standard "blocks" of 9-10 fields per block, and the observer chooses blocks on the fly throughout the night, prioritizing areas of the sky that have not recently been covered to V>21.

The 19.4 deg$^2$ field of view of the Schmidt telescope allows the entire visible nighttime sky to be covered in 3-4 days, depending on the time of year, and exclusion zones for the Milky Way and moon. A custom nightly planner was developed to automate the scheduling. All-sky coverage is prioritized, as far north as Dec. +75, and down to solar elongations as low as 55 degrees. A 4-night coverage cadence is illustrated in the banner at the bottom of the page.

## Discovery Statistics




*Discovery statistics of all NEO surveys through April 2017. Courtesy JPL.*

2016 was a record year for NEO discovery. 1,889 new NEOs were cataloged, of which CSS discovered 930: an increase of 64% over the CSS total for the previous year. The spike in CSS's productivity is directly attributable to the installation of the new camera at the 1.5-m. While the new Schmidt camera is still in the final stages of commissioning, it has shown its potential by discovering five NEOs on a single clear night near new moon. The discovery rate through the first quarter of 2017 suggests an even more productive year is underway.

## Software Upgrades

Recent software upgrades include the use of better centroiding algorithms, and astrometric fitting routines that take advantage of reference stars across multiple survey images. Astrometry submissions are being prepared according to the new IAU standard Astrometry Data Exchange Standard (ADES), including the addition of positional error estimates. The CSS processing pipeline has been made more sensitive, more flexible and more robust over the years. Since 2013, sensitivity to moving objects has increased by 20-30% due to significant rewriting and careful tuning. We have also demonstrated the successful detection of moving objects in data sets from other telescopes, including the DECam mosaic on the CTIO 4.0-m Blanco telescope, and the MapCam instrument on the OSIRIS-REx spacecraft.

## Archival Reprocessing + PDS Hosting

CSS is in the process of leveraging these pipeline improvements by reprocessing our archival holdings, going back to 2003. The CSS archive consists of over 3 million images spanning 40 telescope-years of data from four telescopes: the three currently operational telescopes plus the Siding Spring Survey (conducted on the 0.5-m Uppsala Schmidt in collaboration with the Australian National University), which ran from 2004-2013.

CSS astrometry accounts for over a quarter of the Minor Planet Center observation database: over 46 million individual astrometric positions. Approximately 98% of the known asteroids contain data from at least one CSS telescope. By re-measuring the data with a more sophisticated pipeline, we will provide data that can be used to improve the orbits and extend the observed arcs of hundreds of thousands of asteroids.

The reprocessed data will be delivered to the NASA Planetary Data System (PDS) Small Bodies Node, where it will be permanently archived and served to the public. Contemporary survey and follow-up data from CSS telescopes will also be delivered to PDS on an ongoing basis, potentially becoming available to the public the day after it is obtained. Next-day data delivery to PDS is nominally scheduled to begin during the 4$^{th}$ quarter of 2017, with reprocessed archival data flowing to PDS starting in 2018.

## Acknowledgements

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