The Catalina Sky Survey:

Networked NEO Survey and Follow-up

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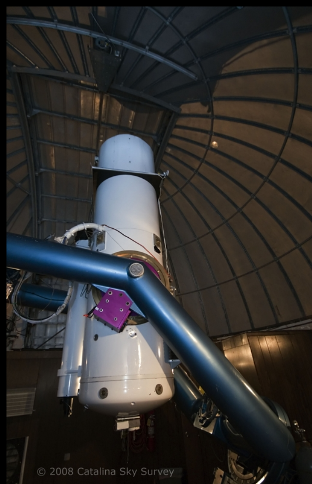
Catalina Sky Survey

- NASA-funded NEO search and follow-up program, operational for 20 years
- There are 17,500 known NEOs; CSS has discovered >45% of the catalog
- CSS discovered 990 NEOs in 2017 – more than any other program, in any year
- Key to CSS's discovery success is significant attention to follow-up

Catalina Sky Survey



Survey telescopes –
0.7-m Schmidt (703) and 1.5-m (G96)

Follow-up telescopes –
1.0-m (I52) and Kuiper 61” (V06)

Left: Siding Spring 0.5-m Schmidt (E12)
2004 – 2013 (decommissioned)

Right: CSS operations workstation

Catalina Sky Survey

- CSS is already running a network of highly automated telescopes:
  - Survey field selection + scheduling is automated (custom nightly planner and queue manager)
  - Follow-up target selection criteria well-defined, scripted
  - Little human interaction needed for data collection, scheduling, focusing, etc.
  - Tight coupling between instrument and telescope (interleaved camera readout, step + settle)
  - Telescopes are loosely coordinated with each other - complementary roles are defined
  - Open shutter efficiency is routinely ~75%, taking 800-1,000 images per night
  - One telescope (I52) is remotely operated by an observer at one of the survey telescopes

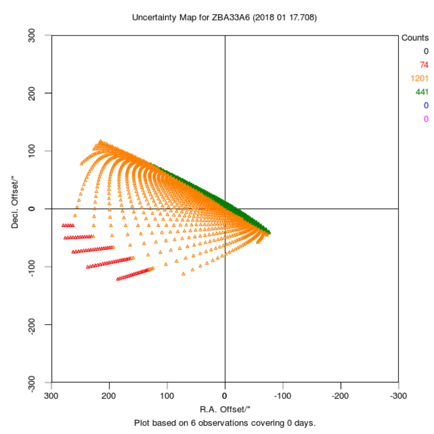
NEO life cycle

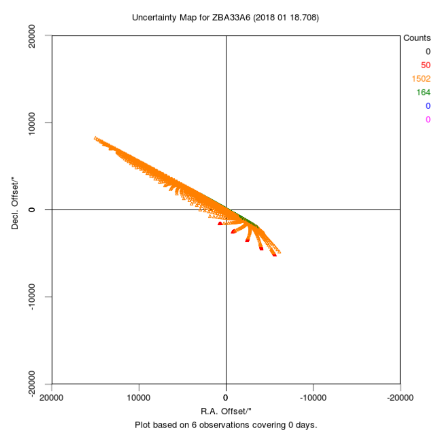
- NEO discovery is not granted until a unique initial orbit can be calculated
- Discovery requires an initial detection + report, followed by days of follow-up observations *
- Discovery requirements:
  - Initial detection and report, t = 0
  - Same-night follow-up observations, t = 1h - 6h
  - Subsequent night follow-up observations, t = 1d … 3d
- Post-discovery follow-up requirements:
  - Discovery apparition arc extension, t = 10d ... 90d
  - Subsequent apparition recovery, t = 1y ... 10y
  - 3-4 apparitions required for numbering

* observations = astrometry. RA, Dec, Time, approximate magnitude, observer location

NEO life cycle

- Cadence of follow-up observations driven by sky-plane uncertainty. Collapse the uncertainty, or lose the object!
- Around ~10% of initial NEO detections do not get enough follow-up to qualify for “discovery”. The most critical time for follow-up is the first 24 hours after initial detection.





Fast-moving (10 deg/day) NEO discovered by CSS Jan. 17 2018, and followed up ~1 hour later. Uncertainty after 12 hours is 5 arcmin. Without follow-up, uncertainty grows to ~3 degrees after 36 hours.

NEO ecosystem

- Hundreds or thousands of NEOs in need of observations at any time:
  - 17,500 known NEOs in the catalog, discovery rate of 2,000+ NEOs per year
  - 50-200 new NEO candidates in need of confirmation / follow-up on any given night
- Demand for urgent NEO follow-up is largely driven by survey productivity
  - There is demand for NEO observations every night, generally peaking after midnight
  - There is demand for NEO observations every lunation, generally peaking after new moon

ARTN Telescope / Instrument requirements for NEO follow-up

- Wide-field imager (30’ – 60’ ideal), monolithic detector preferred.
  - Smaller FoVs (e.g. 9’ Mont4K) acceptable for many, but not all potential targets
- Plate scale: ~1 arc second pixels acceptable
- No filters necessary – need to maximize flux.
- Non-sidereal tracking, from 0.1 to 10+ deg/day
- Low imaging overheads (camera readout, step + settle, calibrations). Most observations will be short (<2 min.)
- Accurate observation timing (~5 ms) – high-precision clock tied directly tied to shutter open/close

ARTN Scheduling / Network requirements for NEO follow-up

CATALINA SKY SURVEY

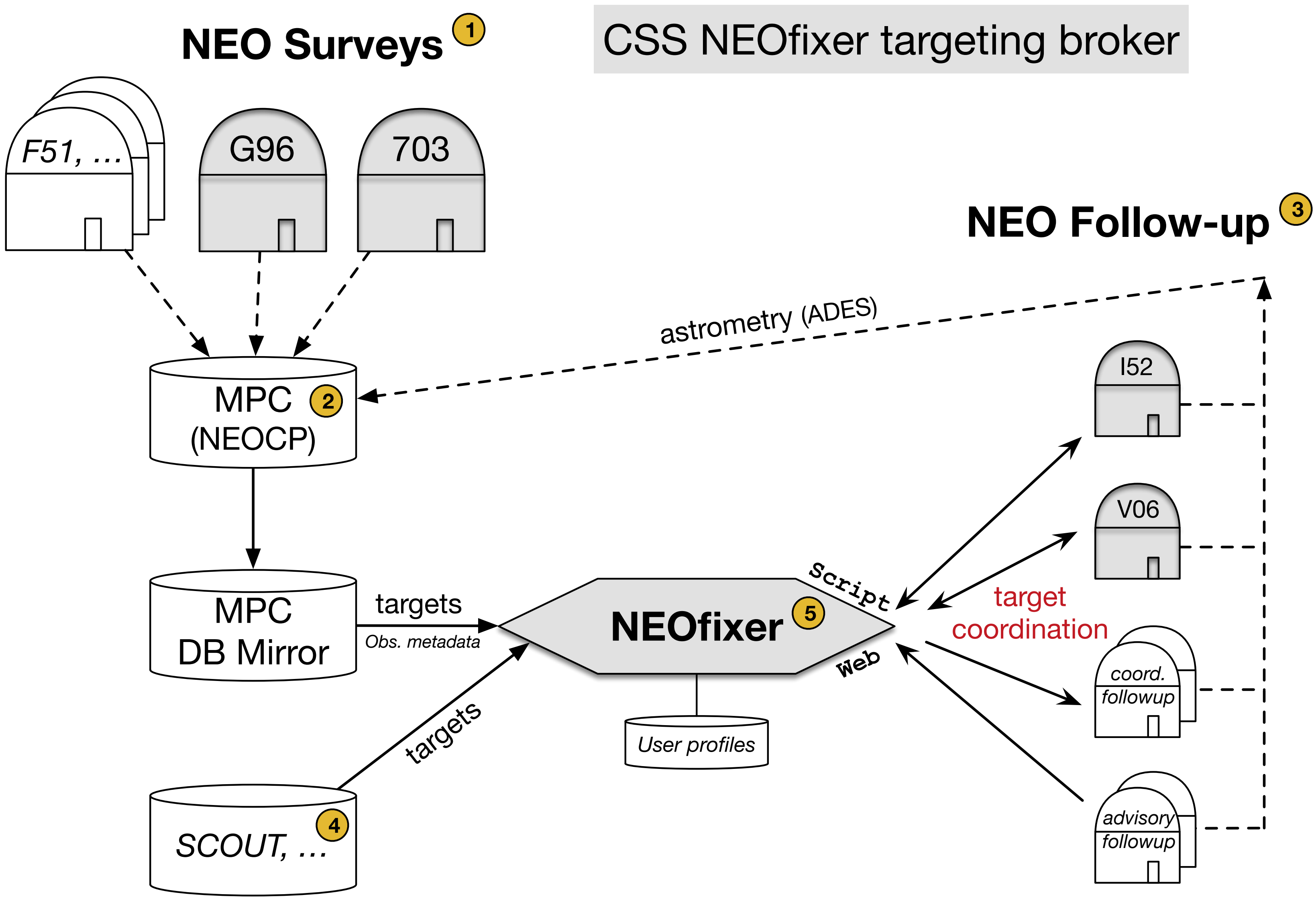
- Cadence : 3-5 images (or stacks), spaced to detect object motion.
  - A single object might need only ~5 minutes of on-source time, evenly spaced over 45 minutes. Can be interleaved with other objects / programs
  - CSS nomenclature: image is fundamental unit; an observation is one or more images; a group may include multiple observations.
- Ability to define observing windows – *"don't start before time X, and make sure to finish it before time Y"*
- Ability to prioritize target importance relative to other NEOs, and relative to other non-NEO programs
- Low latencies from scheduling request to data collection (tens of minutes), and from data collection to delivery (minutes). Immediate reporting of astrometry is critical.

NEOfixer

- Target broker for NEOs, under development
- Answers the question, *"what is the most useful observation I can make with my system right now?"* (or at time X)
- With community buy-in, NEOfixer will balance follow-up load across sites, preserving discoveries that would otherwise be lost, and maximize the orbit improvement benefit to the NEO catalog
- ARTN could interface directly with NEOfixer to fill CSS's allocation in real time.

CSS use of the Kuiper 61”

- 2017B – CSS allocated ~20 nights on the 61”
- We run the 61” “the CSS way”, including:
  - CSS queue manager and acquisition software
  - On-site real-time data processing
  - Custom TCS interface
  - Automated focus model (accounts for temperature and flexure changes)
- This is possible thanks to TCS-ng and a CSS-specific interface to Mont4K from Mike Lesser
- During a typical night we observe 50-90 targets, slewing hundreds of times.
- Minimal direct observer interaction with the telescope or camera
- Open shutter efficiency can approach 70%, though 50% is typical
- Will continue in 2018A – additional ~20 nights allocated



NEO Surveys 1
CSS NEOfixer targeting broker
F51, ...
G96
703
NEO Follow-up 3
astrometry (ADES)
MPC 2
(NEOCP)
I52
V06
MPC
DB Mirror
targets
Obs. metadata
NEOfixer 5
Script
Web
target
coordination
coord.
followup
User profiles
targets
SCOUT, ... 4
advisory
followup