The Population of Near-Earth Asteroids and Current Survey Completion

Alan Harris

MoreData! Inc.

Target NEO 2

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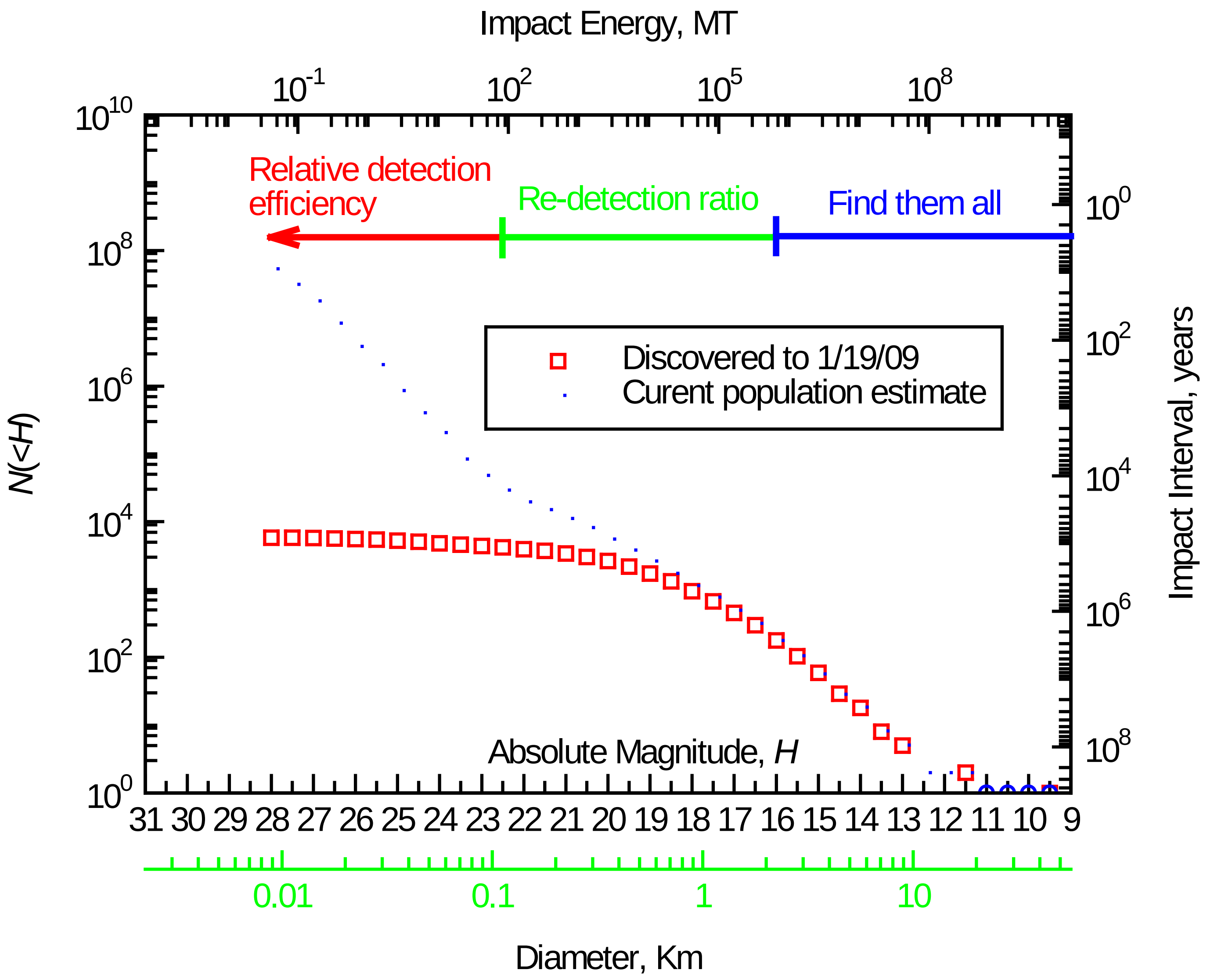
The slides that follow are essentially material presented at the Planetary Defense Conference, April 14-19, in Flagstaff, AZ. I provide them here as background material to describe the methodology of assessing survey completion and estimating the NEA size-frequency population.

Main points for this conference

- The survey simulation methodology described, applied here to ground-based surveys, is very general and can be (and has been) applied to space-based surveys in thermal IR as well as visible passbands.
- The reduction in parameters by introducing $dm = V_{lim} – H$ as the independent variable in computer simulations is very powerful, not only in reducing the volume of computations, but also in providing better statistics over a wide range of size (*H*), and avoids assuming a size-frequency distribution in advance. Using *dm* in this way to represent a wide range of *H* magnitude implicitly assumes that the distribution of orbits of NEAs is homologous (the same) over the range of size (*H*) investigated.
- Estimating completion from the ratio of re-detections to new discoveries for a test interval (2 years in our estimates) is generally superior to attempting to monitor sky area covered, cadence, limiting magnitude, etc. of a real ground-based survey. This may not be the case for evaluating completion of a space-based survey, both because conditions are more constant and controlled in space, and because of the long time baseline needed to accurately estimate re-detection ratios.

NEA Population: How do we know?

When a survey keeps re-detecting the same objects without finding any new ones, one can infer that the survey has found them all. Going to smaller sizes, one can estimate the fraction discovered from the ratio of re-detections to total detections. Still smaller, where there are insufficient re-detections, one can estimate the relative detection efficiency versus size, and extrapolate the population estimate to still smaller objects.



Completion and Re-detection Ratio

If all asteroids of a given size were equally easy to detect, then the completion in a given size range would simply be the ratio of re-detected asteroids to the total number detected (new plus old) in a trial time interval.

The total population in that size range would be simply the number known divided by the completion (re-detection ratio). For example, if 200 asteroids in a given size range were already known, and in the next couple years 50 of those were re-detected by a survey and 50 new ones were discovered, we would infer the completion was 50%, and the total population would be 400.

But asteroids are not all equally easy to discover, due to the range of orbital parameters resulting in, among other factors, variable intervals of observability over time.

In order to obtain an accurate estimate of true completion, and thus population, one must bias-correct the observed re-detection ratio to estimate the true completion as a function of size of asteroid. We do this with a computer model simulating actual surveys.

Computer Survey Simulations (1)

We generate a large number of synthetic NEA orbits matching as best we can the distribution of orbits of large discovered NEAs, where completion is high so that biases in the orbit distribution should be minimal. Rather than assign sizes to the synthetic asteroids, we define a parameter dm as follows:

$$dm = V_{\mathrm{lim}} - H$$

where V_{lim} is the limiting magnitude of the survey and H is the absolute magnitude of interest.

In the first step of a simulation, we compute the sky positions and other parameters that affect visibility (rate of motion, solar elongation, phase angle, galactic latitude, etc.) for each orbit (100,000) every few days for ten years. We tabulate these parameters, along with what would be the sky magnitude V, less absolute magnitude:

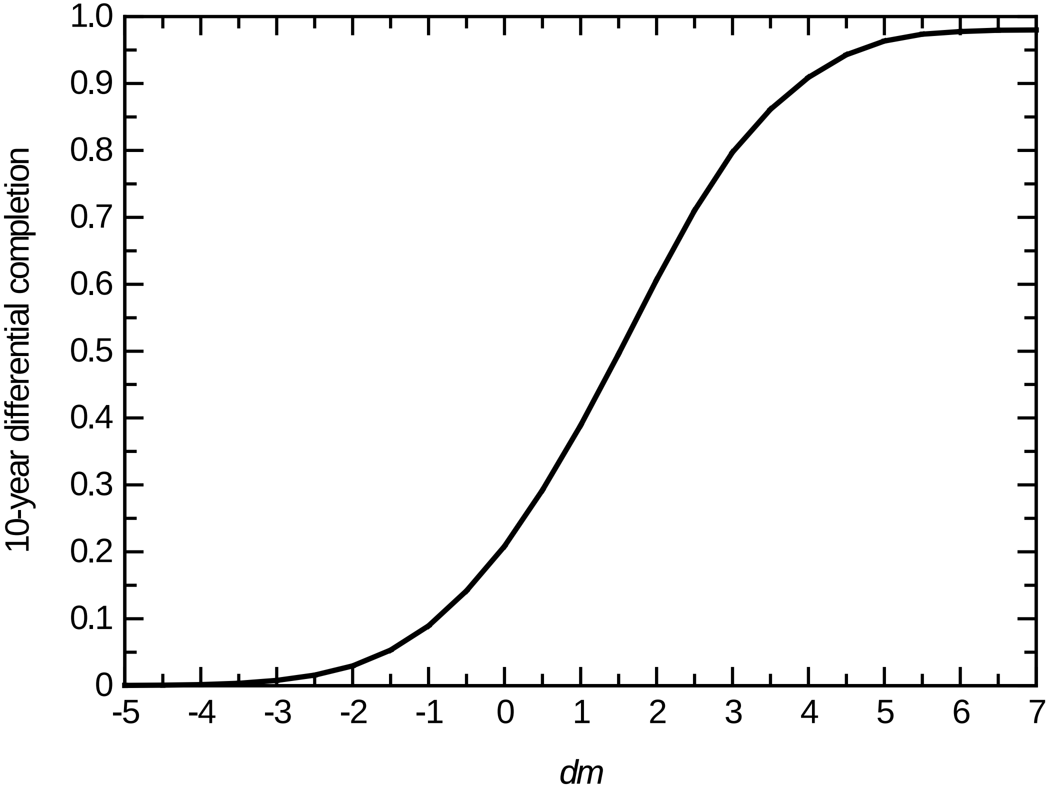
$$dm' = V - H = 5\log(r\Delta) + \Phi(\alpha)$$

where r and Δ are Earth and Sun distances and $\Phi(\alpha)$ is the phase relation for solar phase angle α.

Computer Simulation (2)

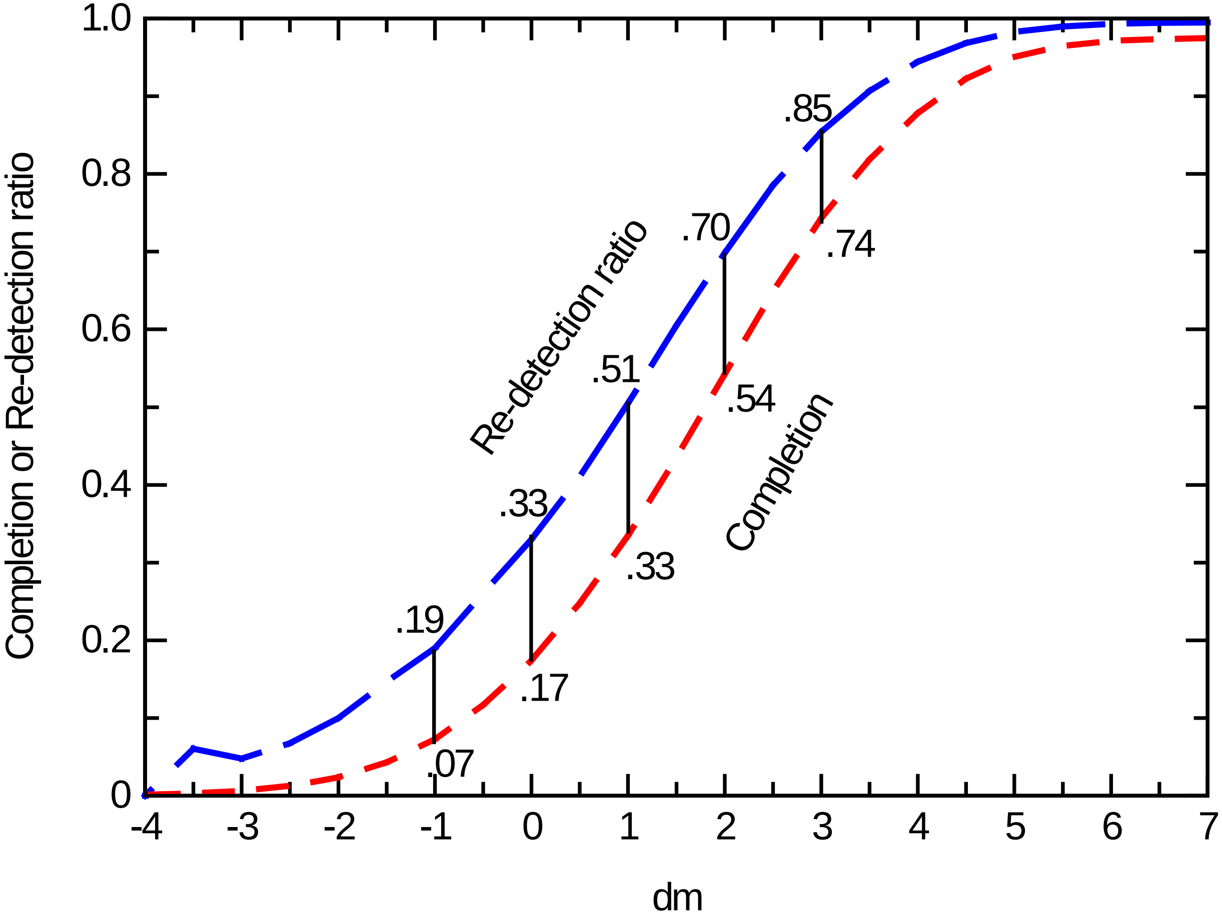
The massive "observation file" need be generated only once. For a specific simulation, we can specify a particular observing site, the area of sky to be covered, observing cadence, specific limits on declination, solar elongation, etc., and even impose modifications on dm' to account for expected magnitude loss due to zenith distance, trailing loss, sky brightness, seeing, etc. We can also specify how many detections over how much time constitutes a successful "discovery".

For each "observation" where it is determined the object is in the field observed, a detection is scored if $dm' < dm$. The same observation file can be "scanned" repeatedly using different values of dm to build up a completion curve as a function of dm.



Model Completion vs. Re-detection Ratio

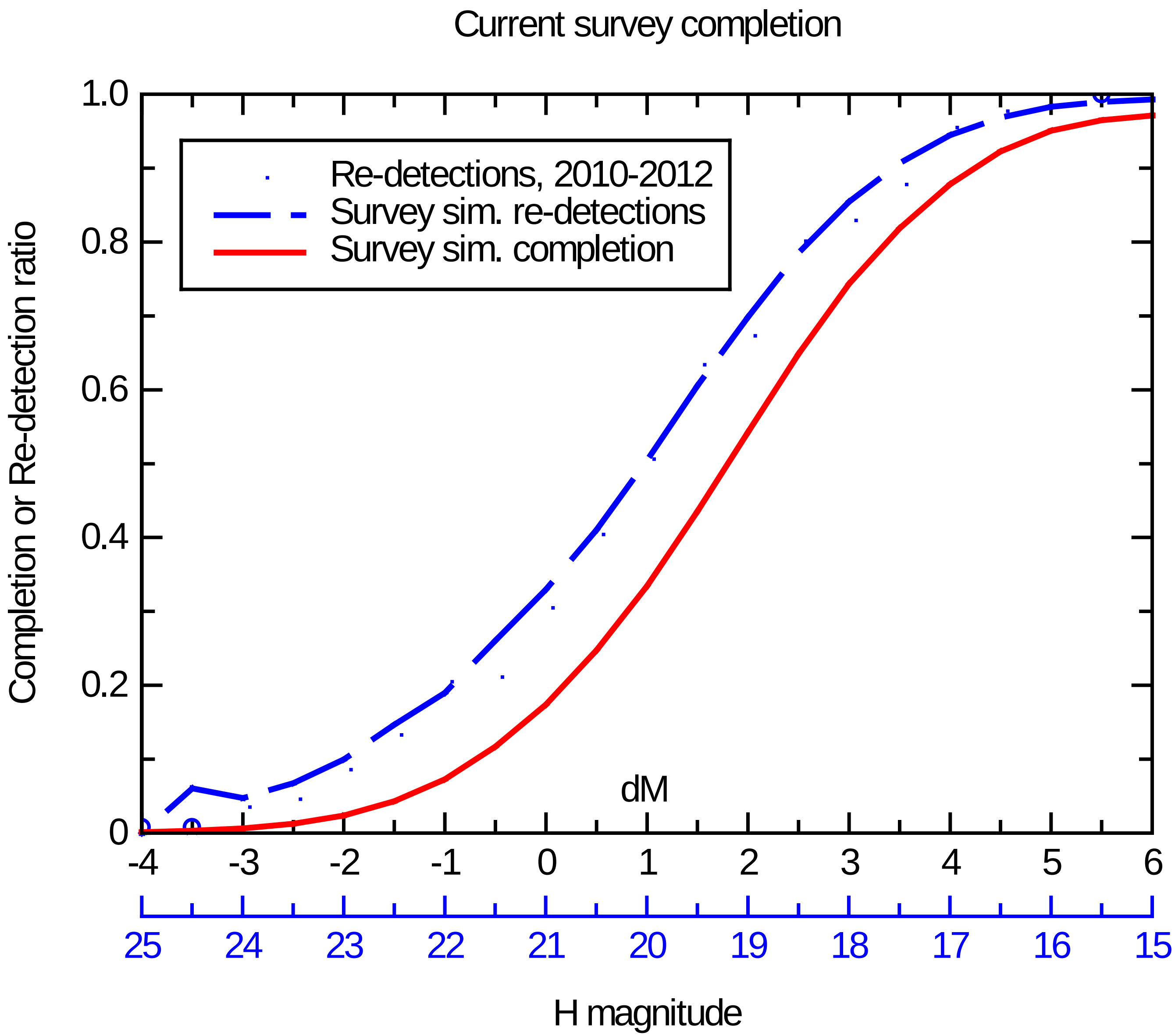
Unlike a real survey, in the computer simulation, we know the total population, so we can run a simulation, say for ten years, and also track the re-detection ratio for a trial interval, say the last two years of the simulation. Thus we can plot and compare the actual (model) completion along with the re-detection ratio.



After ten years or so of simulated survey, the shape of the completion curve is remarkably similar over a wide range of survey parameters; it mainly just moves to the left as time progresses.

Furthermore, the Re-detection ratio is similarly stable, tracking about 1.0 magnitude lower value of dm.

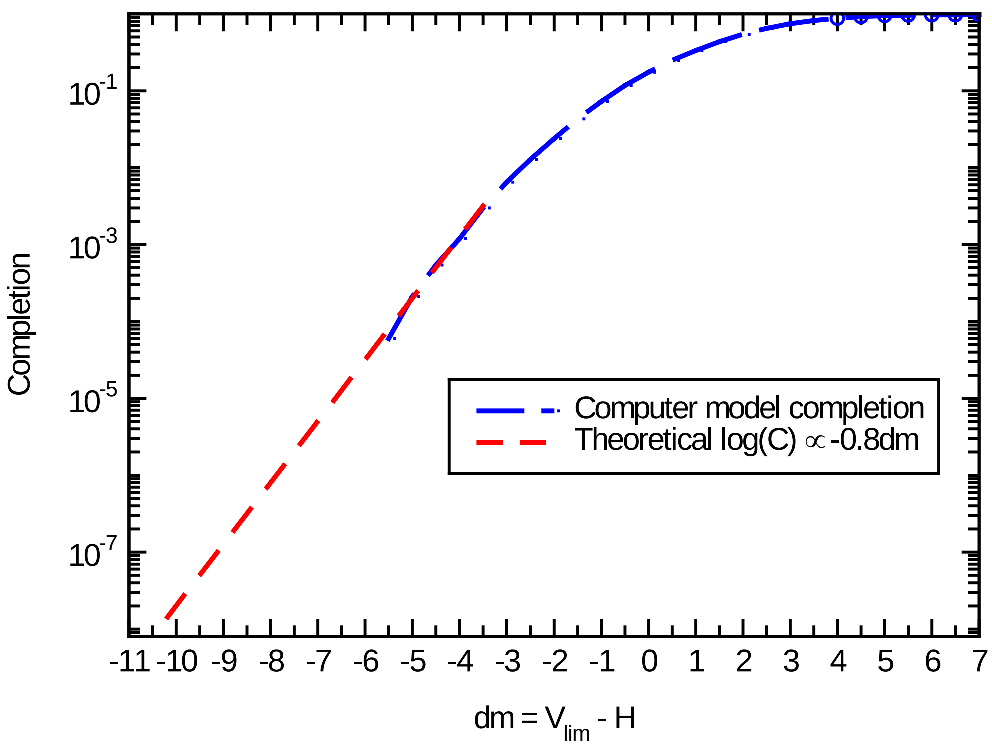
Model vs. actual survey re-detection ratio



The actual re-detection ratios for the combination of LINEAR, Catalina, and Siding Spring match the model curve within the uncertainties in the survey data. We thus adopt this model completion curve as representing current survey completion.

Extrapolation to smaller size

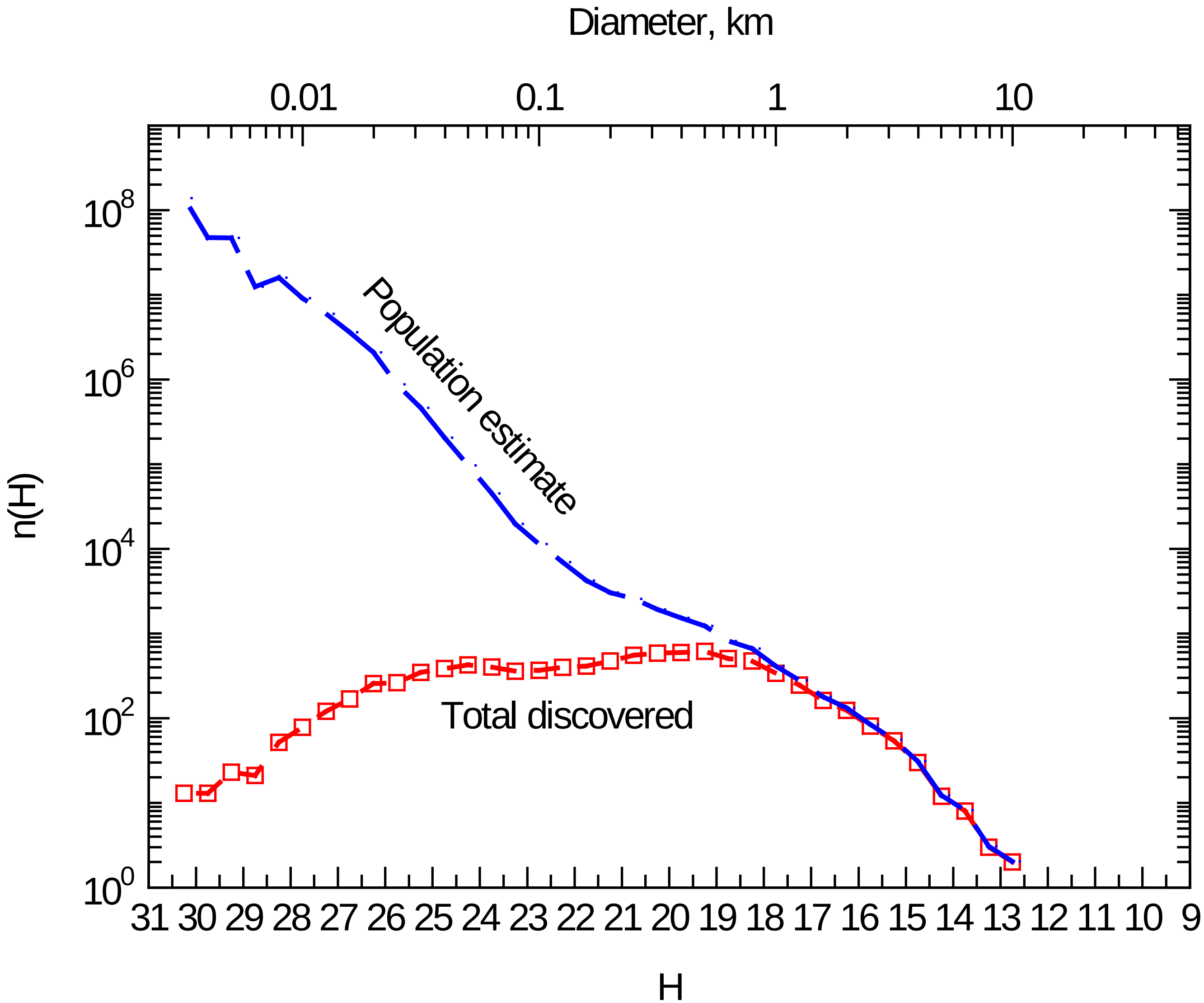
The observed re-detection ratio becomes uncertain below about 0.1 (that is, H greater than about 22) due to the low number of re-detections. However, having “calibrated” the completion curve in the range of good re-detection statistics, we can extend to still smaller sizes by assuming that the computer completion curve accurately models actual completion. This works until the number of “detections” in the computer model falls below a statistically useful number, say about 100 “detections” out of the 100,000 model asteroids, or a completion of about 10^{-3}. This corresponds to about dm = -4.0, or on the scaled curve to about H = 25.0.



Fortunately, below dm of ~3.0, detections are close to the Earth and can be modeled with rectilinear motion rather than accounting for orbital motion. An analytical completion function can be matched to the computer completion curve and extrapolated to arbitrarily small size.

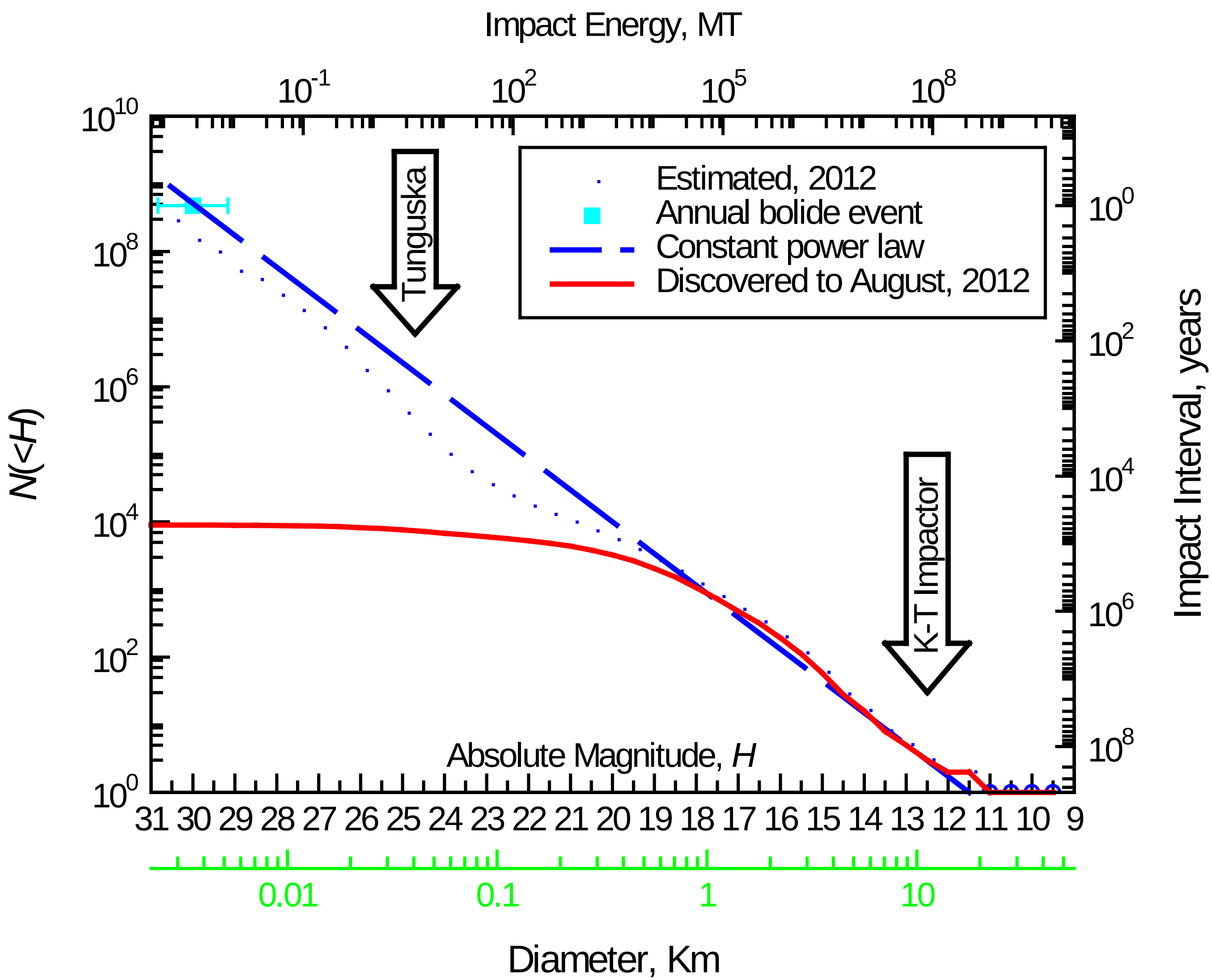
With these extensions, we now have an estimate of completion over the entire size range of observed objects.

Differential Population



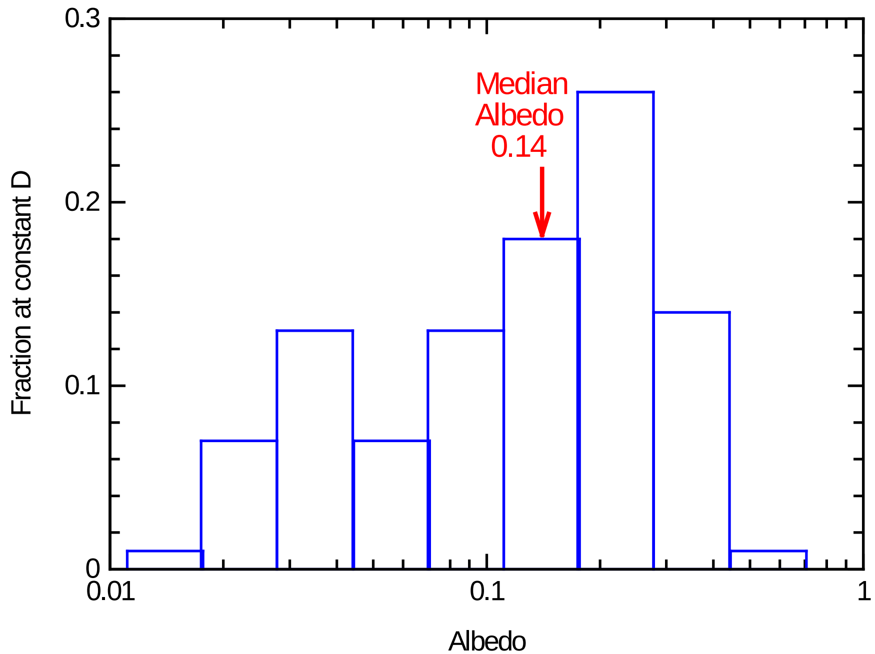
Plotted here are the numbers in each half-magnitude interval, in red the total number discovered as of August 2012, and in blue the estimated total population in that size range, based on the completion curves of the previous graphs.

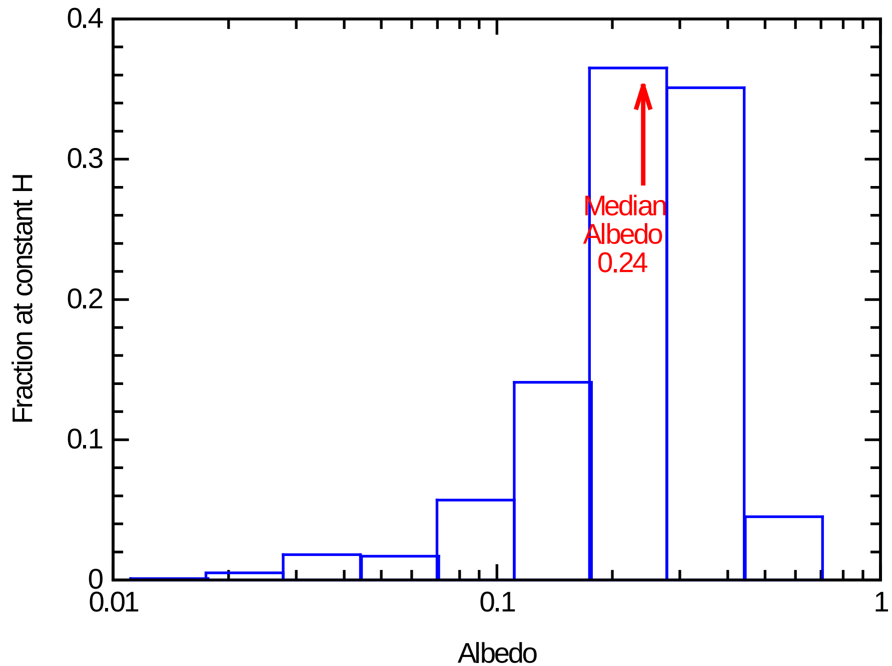
Cumulative Population



The cumulative population is the running sum of the differential population, from the previous plot. The number *N* is the total number of NEAs larger than the specified size (*H* or Diameter).

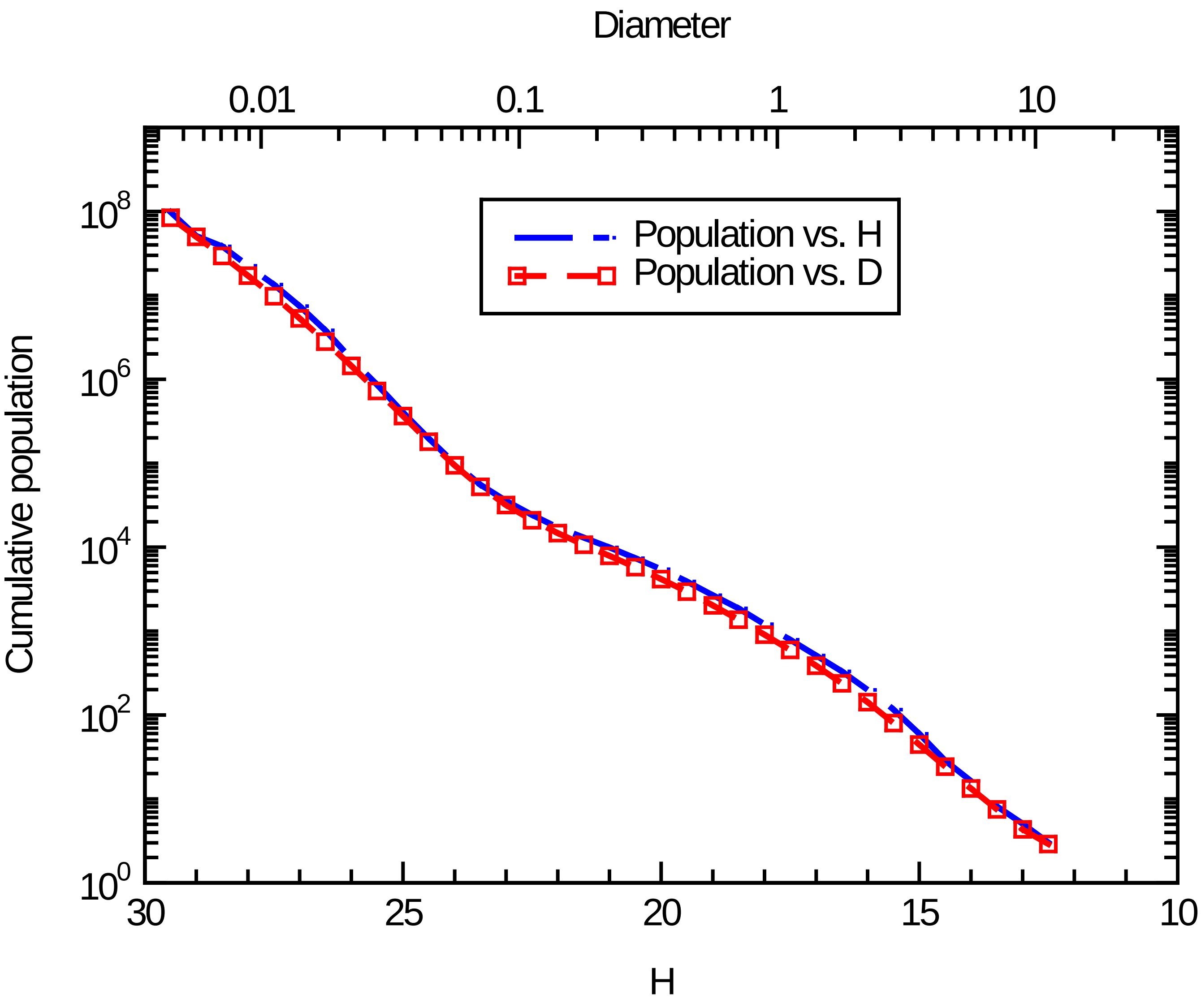
$N(<H)$ vs. $N(>D)$: Mean albedo





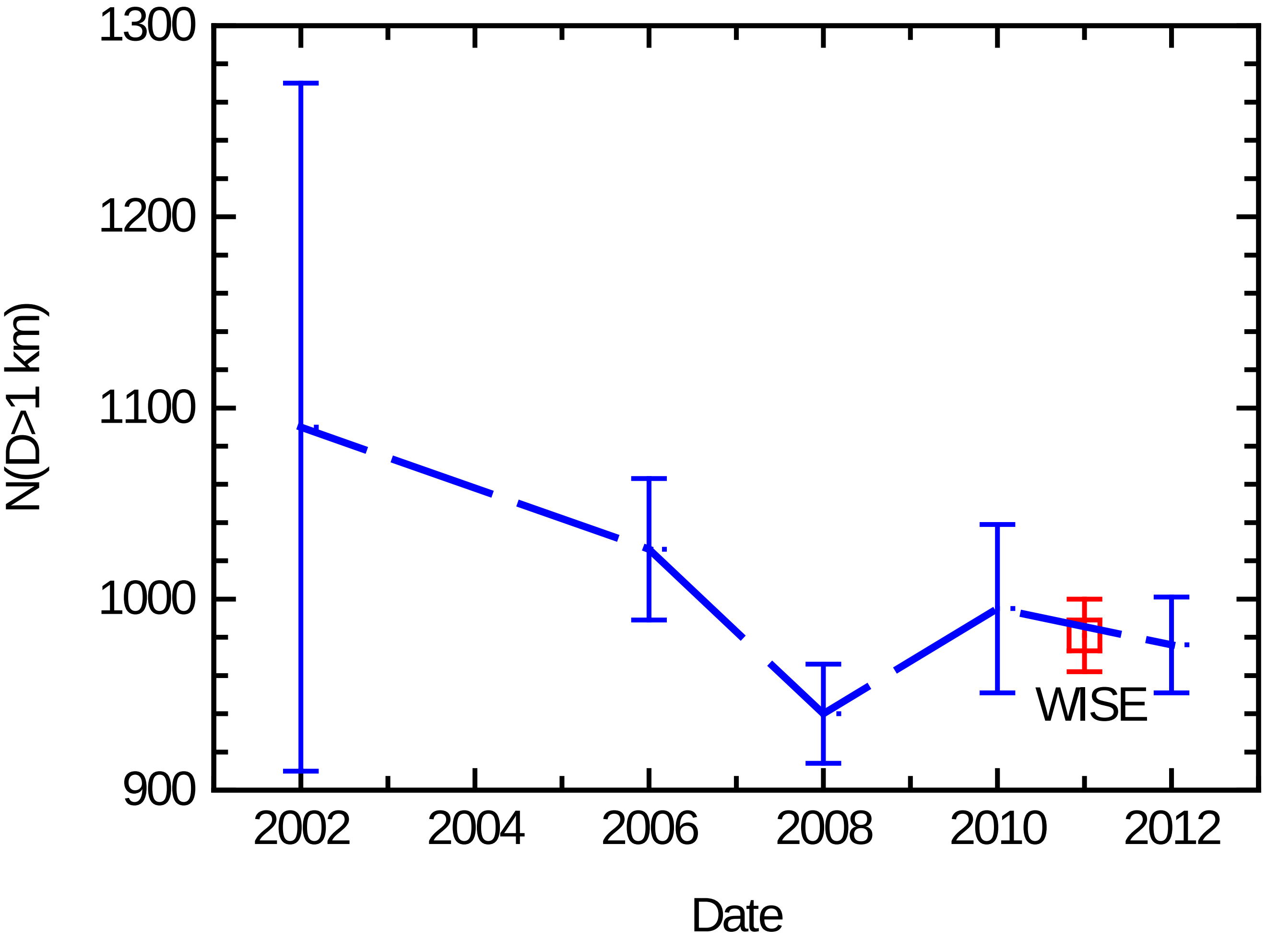
The figure on the left shows the NEA albedo distribution as determined by WISE. Since thermal IR detection does not depend much on albedo, this distribution closely represents the distribution of albedo at a given diameter. Because of the steeply sloping size-frequency distribution (in either *D* or *H*), there are far more high albedo (hence smaller) asteroids in a distribution at a given *H* magnitude, as shown on the right. This distribution more closely matches the distribution of albedos of NEAs discovered by optical surveys.

Comparison of *N*(<*H*) vs. *N*(>*D*)



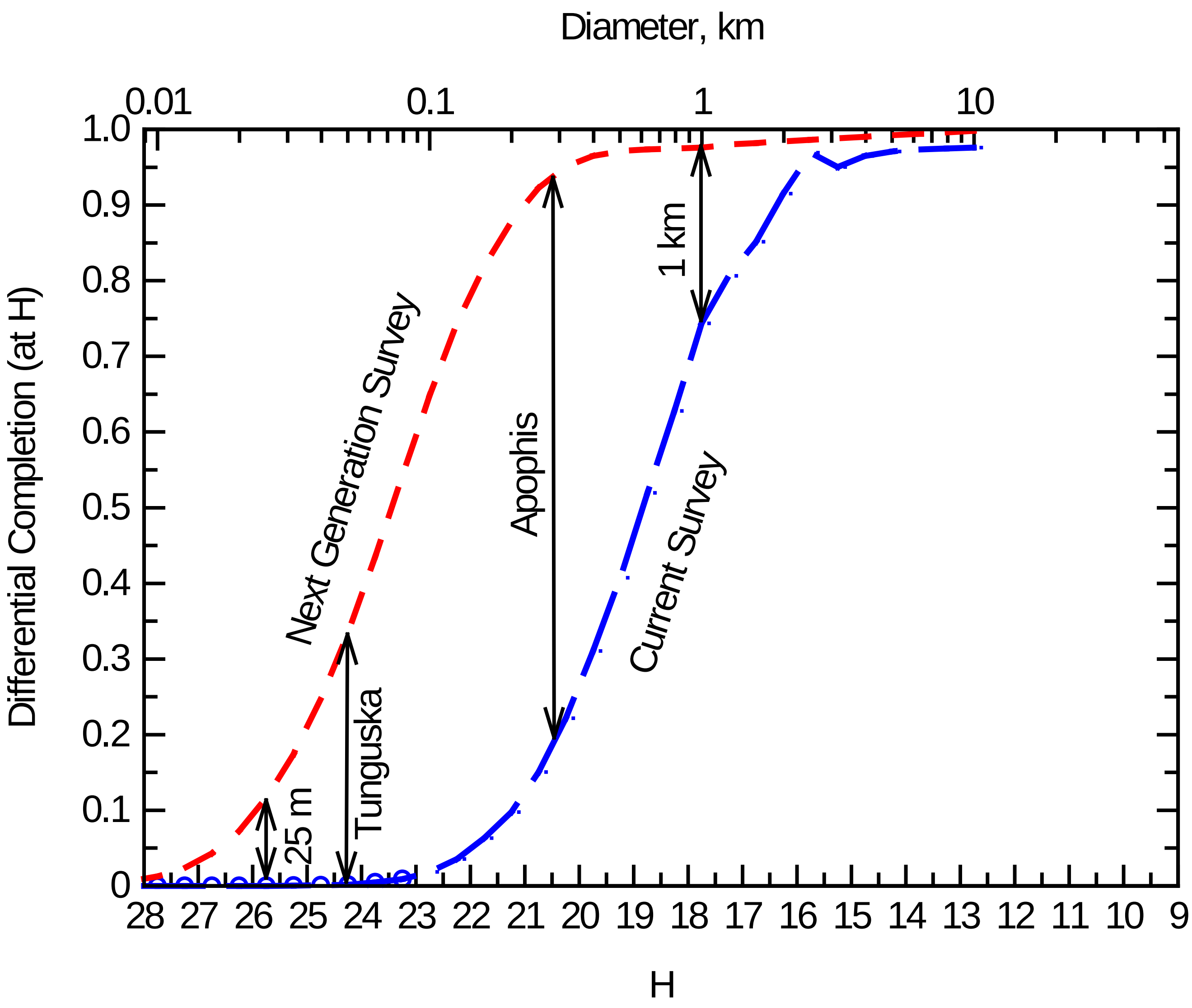
When the size-frequency distribution is transformed from *N*(<*H*) to *N*(>*D*) using the albedo distribution from the right panel of the previous slide, the difference from the *N*(<*H*) distribution is less than the uncertainty of the estimated population.

Population estimates over time



For the last decade, I have been updating my estimate of the population of NEAs, N(D>1km), every couple years, as the survey progresses. The last few estimates have been quite stable, and in close agreement with the recent estimate by WISE.

Current and Future Survey Completion



This plot shows the completion vs. size at current survey level, and as expected for a survey that achieves 90% integral completion to a size of D > 140 m.

Summary

- Latest (2012) estimated population of NEAs is little changed from 2006, 2008, and 2010 estimates:
  - $N(H<17.75) = N(D>1km) = 976 \pm 30$
  - $N_{disc}(H<17.75) = 849$ as of August 2, 2012; Completion = 87%
  - Size-frequency distribution still has dip in 50-500 m range, estimated population over the entire range is little changed.
- Next-Generation surveys to reach C(D>140m) of 90% will in the process:
  - Complete the survey to sensibly 100% of objects D > 1 km
  - Catalog and track >90% of “Apophis” sized objects
  - Discover ~1/3 of “Tunguska” sized objects and ~10% of anything large enough to make it to the ground (D > 25m)
- Current surveys have almost a 50% chance of detecting a “death plunge” small object with enough time for civil defense measures; future surveys have the potential to do even better with appropriate observing protocol.