FINDING KBO FLYBY TARGETS FOR NEW HORIZONS

JOHN SPENCER and MARC BUIE
Lowell Observatory

LESLIE YOUNG
Southwest Research Institute

YANPING GUO
John Hopkins University Applied Physics Laboratory

ALAN STERN
Southwest Research Institute

Abstract. Development of the New Horizons mission to Pluto and the Kuiper Belt is now fully funded by NASA (Stern and Spencer, this volume). If all goes well, New Horizons will be launched in January 2006, followed by a Jupiter gravity assist in 2007, with Pluto arrival expected in either 2015 or 2016, depending on the launch vehicle chosen. A backup launch date of early 2007, without a Jupiter flyby, would give a Pluto arrival in 2019 or 2020. In either case, a flyby of at least one Kuiper Belt object (KBO) is planned following the Pluto encounter, sometime before the spacecraft reaches a heliocentric distance of 50 AU, in 2021 or 2023 for the 2006 launch, and 2027 or 2029 for the 2007 launch. However, none of the almost 1000 currently-known KBOs will pass close enough to the spacecraft trajectory to be targeted by New Horizons, so the KBO flyby depends on finding a suitable target among the estimated 500,000 KBOs larger than 40 km in diameter. This paper discusses the issues involved in finding one or more KBO targets for New Horizons. The New Horizons team plans its own searches for mission KBOs but will welcome other U.S, or international team who wish to become involved in exchange for mission participation at the KBO.

1. The Number of Accessible KBOs

We first determine how many KBOs of a given size or magnitude are likely to be accessible to the New Horizons spacecraft, given the amount of fuel available for targeting (measured in Δv, the velocity change that the fuel can provide). We assume the KBO sky density vs. brightness relation from Gladman et al. (2001) $N = 10^{0.69(M-23.5)}$, where M is R magnitude and N is the KBOs per square degree brighter than that magnitude. Luu and Jewitt (2002) propose an only slightly different power law ($N = 10^{0.64(M-23.23)}$) which results in a very similar sky density of magnitude 26–27 objects. Neither set of authors sees strong evidence for a break of slope at small sizes to a shallower power law (as might be expected from a transition to a collisional size distribution), which would reduce the number of faint objects, at R magnitudes brighter than 26.
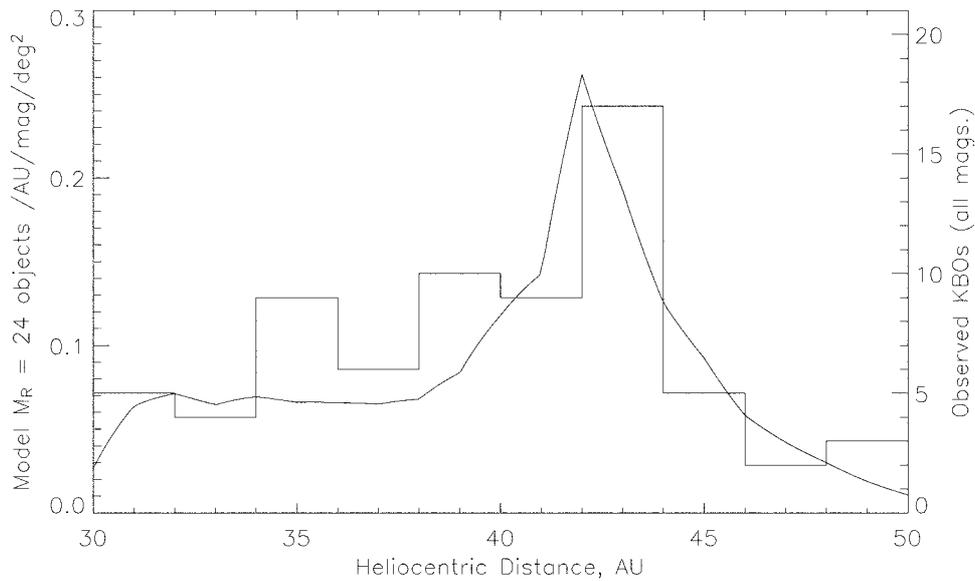
Figure 1. Comparison of the expected heliocentric distance distribution of objects discovered in a magnitude-limited survey, based on our KBO radial distribution model (smooth curve, left axis), to the actual radial distribution of objects with well-determined orbits, obtained from the 2003/04/25 version of the list maintained by Marc Buie at http://www.lowell.edu/~buie/kbo/kbofollowup.html (histogram, right axis). The good quality of the match indicates that our model radial distribution is realistic.

We therefore assume that a single power law applies down to magnitude 27, though observational constraints on the abundance of KBOs fainter than magnitude 26 are currently very poor. The results of new deep surveys from Subaru (Kinoshita et al., this conference) and HST (Holman et al., this conference) may soon clarify the abundance of faint KBOs.

To convert the observed luminosity function into a model of KBO abundance as a function of absolute magnitude and heliocentric distance r, we assume the debiased heliocentric distance distribution from Morbidelli and Brown (2002, their figure 6). This distribution is quite well constrained by discovery statistics, because heliocentric distance can be determined more accurately than semi-major axis from a short observational arc. The distribution is strongly peaked in the classical Kuiper Belt, at around 42 AU. Because more distant objects are more accessible to the spacecraft, accessibility depends strongly on the assumed KBO radial distribution. We test the validity of our model by using it to predict the r distribution of KBOs discovered by a magnitude-limited survey (Figure 1). Doing so, we find the relative distance distribution, which is independent of apparent magnitude given our assumption that the slope of the size-frequency distribution is independent of size and distance, is a good match to the observed r distribution of KBOs with well-determined orbits.

TABLE I

Number of KBOs accessible to new horizons: 2015 Pluto flyby.

Limiting M_R	Diameter km ($r = 42$ AU)		# Accessible objects	
	$p = 0.04$	$p = 0.08$	$\Delta v = 80$ m/s	$\Delta v = 200$ m/s
23.5	203	143	0.009	0.057
24.0	160	113	0.020	0.13
24.5	127	90	0.046	0.29
25.0	101	72	0.098	0.61
25.5	81	57	0.22	1.4
26.0	64	45	0.49	3.1
26.5	51	36	1.1	6.9
27.0	40	29	2.4	15
27.5	32	23	5.3	33
28.0	25	18	11.3	70

A given Δv available to the New Horizons spacecraft for a targeting maneuver shortly after the Pluto encounter defines a cone of accessible space extending outward from Pluto, with half-angle $\Delta v/v_e$, where v_e is the radial component of the heliocentric Pluto encounter velocity. For the nominal 2015 flyby, $v_e = 13.8$ km s^{-1}, and the Pluto encounter occurs at 32.9 AU. The spacecraft can thus most easily reach objects in the outer part of the Kuiper Belt, where the cone is widest.

To determine the expected number of accessible objects of a given size, we numerically integrate the density of KBOs of a given apparent magnitude along the cone of accessibility, according to our simple model of the absolute magnitude distribution. The expected number of available objects is shown in Table I. The table accounts for the fact that for a 2015 flyby, New Horizons is 1.7 degrees above the invariable plane, resulting in an expected ~30% reduction in KBO density, according to models and direct observations of the KBO distribution with latitude (Trujillo et al., 2001; L. Wasserman pers. comm). Later Pluto flyby dates put the trajectory closer to the plane, which is crossed by Pluto in 2018, and thus will increase the number of accessible objects.

The number of accessible objects goes as the square of the available Δv, . The fuel and therefore the Δv budget will not be knowable till after launch, as a significant fraction of the onboard Δv budget is allocated to contingency cleanup of spacecraft launch errors, and will only be available for KBO targeting in the event of an accurate launch. Monte Carlo estimates of the amount of fuel available for KBO targeting after the Pluto flyby indicate 115 m/s is a fairly conservative case. Table I shows results of our calculation of the number of accessible KBOs for a plausible range of Δv.
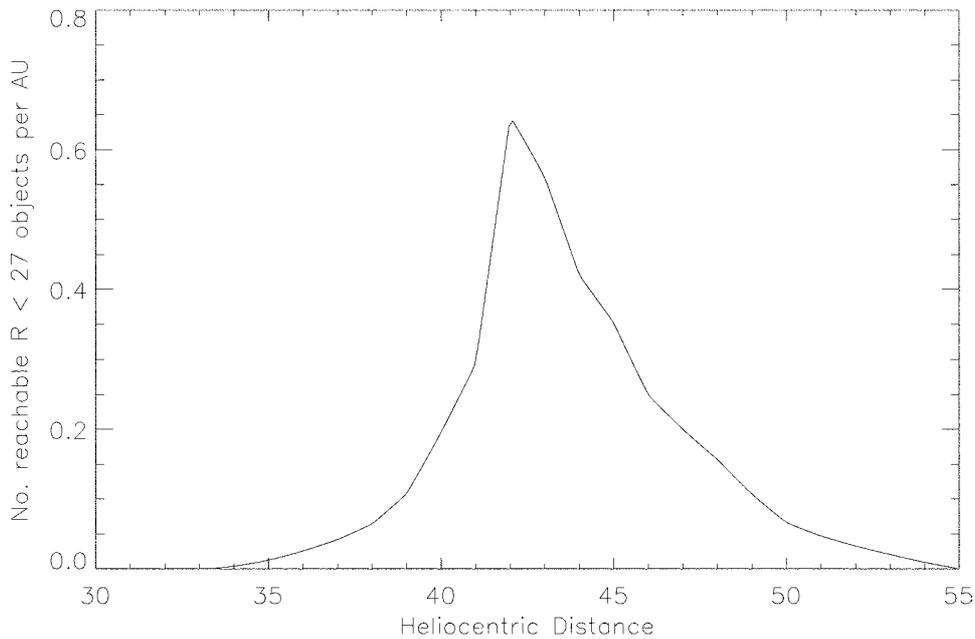
Figure 2. Radial distribution of encounter probability, assuming $\Delta v = 115$ m s^{-1}. The peak in accessibility probability near 42 AU results from the intrinsic peak in KBO density there, sharpened by the narrowness of the accessible cone at small distances, and by the faintness of KBOs of a given size at large distances.

Figure 2 shows the radial distribution of encounter probabilities, which has a strong peak near 42 AU. Table I also shows the diameter, for two plausible values of KBO geometric albedo p, corresponding to the given KBO magnitudes at 42 AU. New Horizons is likely to have a choice of several magnitude 27 objects with a relatively poor launch (lower available KBO Δv), or several magnitude 26 objects with a good launch (i.e., higher available KBO Δv), corresponding to diameters of 29–64 km, depending on albedo.

We also considered the benefits of adjusting the Pluto encounter time to improve our ability to reach a particular KBO. Flexibility in encounter date increases the number of potential KBO targets, because Keplerian shear effectively tilts the cone of accessibility relative to Pluto and the KBO population as the encounter date is varied, providing access to additional objects. However, because the Group 1 (i.e., required) atmospheric radio occultation experiment at Pluto depends on minimizing perturbations of the signal by the solar wind, New Horizons must encounter Pluto within ± 1 month of opposition. For a two-month time window the range of cone tilt is much less than the cone half-angle for plausible Δv, so there is only a marginal increase in the accessible volume. However, if Pluto encounter can be delayed until the following opposition, the combined effects of Keplerian shear of the population, and "diffusion" of objects into and out of the accessibility cone

due to KBO velocity dispersion during the intervening year, results in an almost completely different set of available objects. A one-year flexibility in encounter date, even with encounter constrained to be near opposition, thus almost doubles the number of accessible KBOs for a given Δv, compared to Table I. There is therefore some advantage to searching for bright accessible KBOs before launch, in case a change in trajectory, and thus encounter date, would allow access a particularly interesting object. However, if no such bright object is found, the choice of KBO targets does not need to be made till shortly before the Pluto encounter.

We also performed Monte Carlo simulations of the possibility of multiple KBO flybys for a given Δv. The probability of multiple flybys is a simple function of the number of objects in the accessibility cone and their radial distribution (Figure 2). For a >50% chance of two flybys, the expected number of accessible single objects must be at least 9, and for a >90% chance of a single flyby, the expected number of objects should be at least 2.3.

2. KBO Search Area

As stated above, we have determined that no known KBOs pass close enough to the planned New Horizons trajectory to be potential targets. It is also worth noting that, as we will demonstrate, the current location of expected targets is within the Milky Way, where deep KBO surveys are not normally done. A dedicated search for targets will therefore be required.

To determine the expected search area, we considered KBOs located along the spacecraft trajectory beyond Pluto out to 51 AU, for the nominal 2015 Pluto flyby, and projected their locations back in time from the appropriate encounter date, for a plausible range of orbits. Following Trujillo et al. (2001) we assumed a Gaussian distribution of inclinations, with a half-width of 20°. This model fits the observed latitude distribution of KBOs which is sharply peaked at low latitude (Trujillo et al., 2001; Morbidelli and Brown, 2003). We also follow Trujillo et al., in assuming a uniform eccentricity distribution between 0 and 0.25. We thus do not consider scattered KBOs and other objects with high eccentricity, but as these are a small fraction of the accessible population, their exclusion will not significantly affect the area where most of the objects are found. The number of objects at each heliocentric distance was weighted by the probability of encounter at a given distance as determined from the accessibility cone calculation (Figure 2).

Figure 3 shows the results of this calculation for search epochs in 2004 and 2011. We compare the KBO distribution to the magnitude 16–17 star density distribution in the Milky Way (the faintest magnitudes for which statistics are readily available, from the USNO A2.0 astrometric catalog). Unfortunately the search area corresponds to some of the densest sections of the Milky Way until shortly before the Pluto encounter. Because candidate targets must be observed for 2–3 years to determine a good orbit, targets for the 2015 Pluto flyby trajectory must be identified
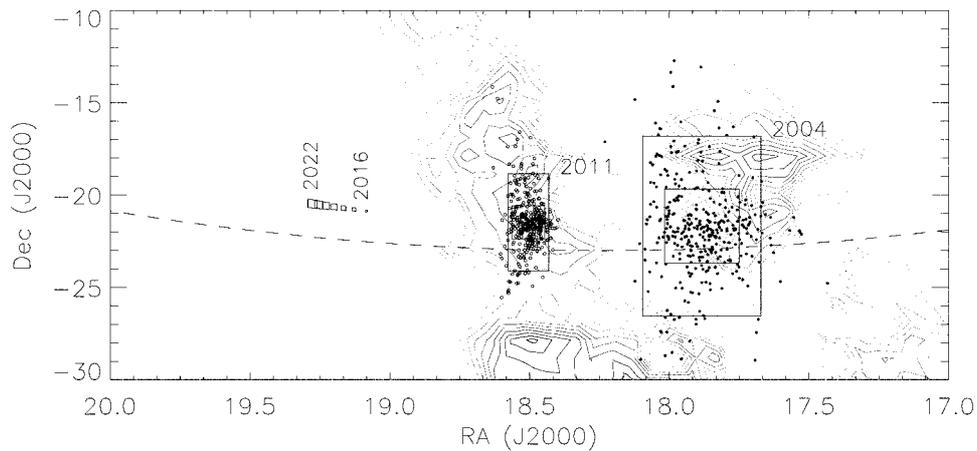
Figure 3. The probability distribution of accessible KBOs on the plane of the sky, for 2004 (solid circles) and 2001 (open circles), for the 2015 Pluto flyby trajectory. The same model objects are shown for each date. The boxes enclosing the objects represent the search area that includes 85% and 50% of accessible objects for each year. The series of small boxes to the left show the size and location on the sky of the accessible region for encounter dates from 2016 to 2022, at yearly intervals, for an assumed Δv of 150 m s^{-1}. Background contours show the relative density of mag. 16–17 stars, with darker contours indicating higher densities. The Milky Way and its central dark dust lane are apparent. The dashed line shows the invariable plane of the solar system.

by about 2012, while the search area is still deep in the Milky Way, though a 2007 launch and 2019 Pluto flyby will allow a later search in less crowded fields. The area to be searched decreases dramatically with time (Figure 4).

Without further study, which we are planning, it is difficult at this time to determine how much the Milky Way will complicate the search effort. It is possible to detect faint moving objects in crowded fields of static objects using various image-differencing techniques, such as those used by Gladman et al. (2001) for pencil-beam KBO surveys, or those used to find variable objects in very crowded Milky Way star fields by the MACHO project (Alcock et al., 2000). While static background objects can be removed essentially perfectly, the photon noise that they contribute to the difference frames will reduce detectability of faint KBOs. Compared to sparse fields, longer effective exposures are therefore needed to reach a given limiting magnitude, but the necessary exposure increase has not yet been quantified for typical Milky Way fields.

3. When to Search?

The best time to perform the search for the New Horizons KBO target(s) depends on several factors. An earlier search gives more time to determine an orbit accurately enough to plan the post-Pluto targeting maneuver, and gives more time to plan the KBO encounter. A search before about 2007 also allows one to take
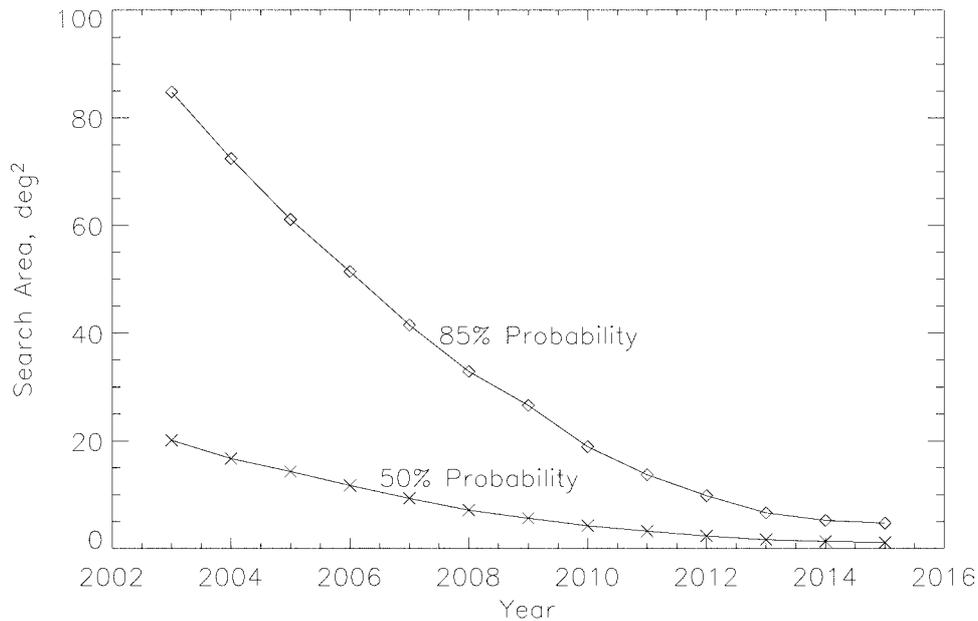
Figure 4. The area occupied by the central 85% and central 50% of accessible KBOs as a function of observation date, for the 2015 Pluto flyby trajectory.

advantage of the reduced background star density in the Milky Way's central dust lanes where most potential targets are currently located (Figure 3). However, a later search needs to only cover a much smaller area (Figure 4), and will allow us to take advantage of expected increases in the availability of large-aperture telescopes, and wide-field detectors. Also, because the orbits of potential targets do not need to be projected so far into the future to determine whether they can be reached by the spacecraft, follow-up orbit determination can be done more accurately and efficiently. The precise spacecraft trajectory, and available onboard Δv, will also not be known until after launch, making identification of potential targets and the precise area that needs to be searched much easier after launch.

Figure 5 shows the estimated time to survey the search area, using a 4-m class telescope with good seeing (the 4-m telescope at CTIO) and an 8-m class telescope with excellent seeing (Subaru on Mauna Kea), assuming that 60% of allocated time, during the time the search area is above airmass 2.0, can be spent integrating on the sky or reading out the camera. We neglected the additional telescope time needed to counteract the effects of background star confusion, as this factor cannot be estimated without further study.

Figure 5 shows that it is not practical to perform a comprehensive search down to magnitude 27 before the 2006 launch of New Horizons, even with Subaru, but to search the region where 50% of accessible objects are likely to be found down to magnitude $\sim$23.7 ($D > 184$ km for $p = 0.04$) at CTIO, or magnitude $\sim$25.5 on Subaru ($D > 81$ km for $p = 0.04$), appears possible in 2004 in just 4
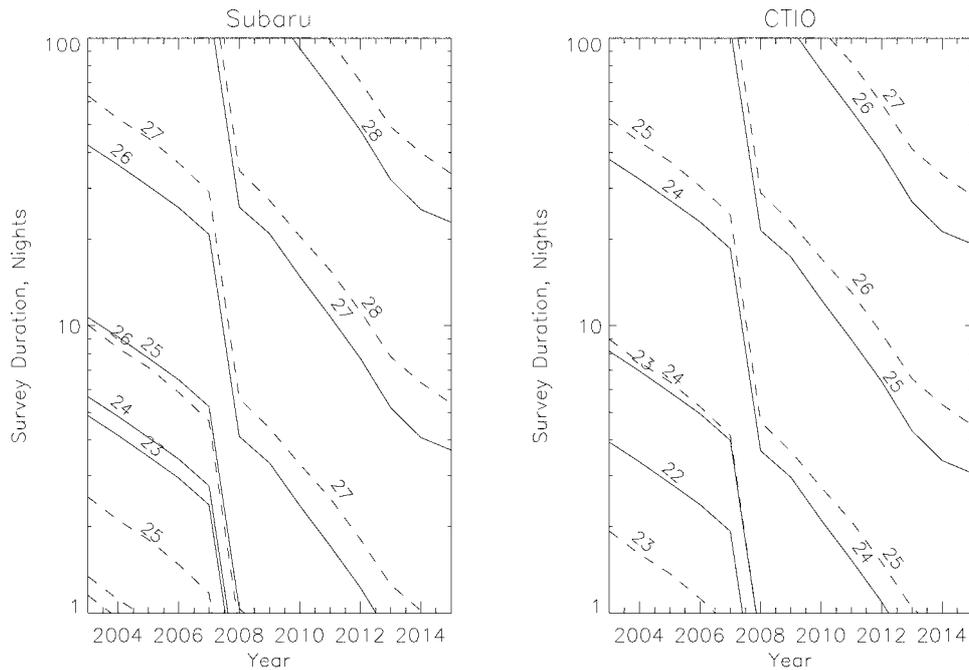
Figure 5. Lower limits to the estimated time needed to survey the area needed to find 85% (solid lines) and 50% (dashed lines) of KBOs accessible to New Horizons down to the given *R* magnitude, for the 8-m Subaru telescope and CTIO 4-m telescope. We assume the SuprimeCam camera on Subaru and Mosaic camera on CTIO (each with a $\sim$0.25 deg^2 field of view) till 2007, and a 1 deg^2 field of view camera thereafter. Times are lower limits because we assume that limiting magnitude is unaffected by confusion due to Milky Way background stars.

nights, neglecting the effects of confusion. If we are lucky enough to have 200 m/s available Δv, and allow a 1-year flexibility in Pluto encounter date, such a search would yield 1.4 expected targetable objects at Subaru and $\sim$0.1 objects at CTIO, neglecting confusion, because the factor of 2 loss arising from searching for only 50% of the objects is offset by the factor of 2 gain from the flexible Pluto encounter date. The probability of success from CTIO is low but the consequences of success, the chance to fly by a large KBO, would be very significant. Assuming that 1 deg^2 cameras are available on 8-meter class telescopes by the end of this decade, a comprehensive search to magnitude 27 around 2011 or 2012 should be possible using such facilities in a reasonable time, and the introduction of even larger cameras would reduce survey time further still. Similar amounts of telescope time will still be required for follow-up and orbit determination of promising candidates.

4. Conclusions

Finding one or more KBO targets for the New Horizons mission is a large but tractable endeavor. We will need to search down to magnitude 27 to be sure of finding at least one target if we are unlucky in the amount of maneuvering fuel available on the spacecraft for KBO targeting, though with plausible fuel budgets, surveys to magnitude 26 may be sufficient. The amount of telescope time required for the survey depends on the severity of the effects of confusion by Milky Way background stars, but it is likely that a comprehensive survey early in the next decade can be done in reasonable time using large-format detectors on 8-meter class telescopes. New Horizons team plans its own searches for mission KBOs but will welcome other U.S. or international teams who wish to become involved in exchange for mission participation at the KBO.

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