TECHNOLOGIES FOR ASTEROID CAPTURE INTO EARTH ORBIT

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We have the technology to capture into Earth orbit any medium to small asteroid that passes sufficiently close to the Earth, as Apophis will do in 2029. A gravitational slingshot greatly amplifies orbital changes, enabling us to control delta-V far beyond our direct capabilities using today's rocket technologies.

Asteroid selection criteria are discussed, along with a few specific asteroid capture opportunities. The possible capture of the asteroid 99942 Apophis is examined in detail, including a proposed mission plan including necessary tools and potential complications.

WHY CAPTURE AN ASTEROID?

The main reason is to gain convenient access to its resources. Even a relatively resource-poor low-iron, low-metal LL chondrite contains 20% iron, significant quantities of water and other volatiles in the form of hydrated minerals, and oxygen to burn.

The asteroid Apophis (likely one of those LL chondrites) contains enough materials to construct about 150 five-gigawatt solar power satellites at 25,000 tons of steel and silicon each, plus Kalpana One style habitats for 100,000 people, all shielded by the slag remaining after iron is smelted out of asteroid ore. The oxygen freed from iron compounds during smelting amounts to well over a million tons more than is needed for the habitats, valuable fuel mass for ion thrusters to move the habitats and solar power satellites into their chosen orbits and to spin them up.

Of course, a space habitat providing food, water, oxygen, fuel, construction supplies, gravity, radiation shielding, and skilled human workers situated above much of the Earth's gravity well is an ideal platform from which to continue the exploration and exploitation of space.

And we should not forget that placing an asteroid into a stable Earth orbit prevents it from colliding with the Earth.

TECHNICAL APPROACH

Even a tiny asteroid masses millions of tons, and we don't yet have the technologies to manhandle them and put them wherever we want. Luckily, we don't have to. When a spaceship or asteroid passes close to a planet or large moon, its orbit is changed, sometimes dramatically.

In principle, the Earth can impart a delta-V of up to 60km/s to an asteroid in orbit around the Sun, although in practice the limits are a small fraction of this. More importantly, small changes in the position or timing of an existing close approach are enormously magnified.

We aren't limited to the Earth, in that close encounters to other planets might be used to alter an asteroid such that it passes close to the Earth at a later time where its orbit can be further tuned by the Earth' gravitational field.

If we can adjust the asteroid's orbit such that it makes a subsequent close approach to the Moon with a relatively low velocity, the resulting slingshot can drop that asteroid into an Earth orbit. The Moon can (in principle) remove up to 2 km/s of velocity relative to the Earth, although less is easier.

A point I'd like to emphasize: Gravitational slingshots are as much art as engineering, especially when considering the variations involved in multiple slingshots around one or more bodies. The people who dreamed up the Cassini and Messenger missions are both geniuses and artists, and I have every confidence that they can find suitable mission plans to capture any potentially hazardous asteroid into Earth orbit, although the missions may be very long and complex thanks to a shortage of appropriate close encounters and/or the need for significant changes to the asteroid's orbital parameters.

ASTEROID SELECTION CRITERIA

The most important consideration is simply the proximity of an asteroid's orbit to a useful keyhole through which the orbital engineers can design a capture mission in a reasonable timeframe with a delta-V that can be achieved at an affordable cost.

The second consideration is the size of the asteroid. Bigger is not better when a 1 kilometer asteroid masses fifty times as much as Apophis, and thus requires a fifty-fold increase in the product of mission time and fuel mass. On the other end, a small 120m LL asteroid massing 2 million tons (and relatively poor in useful metals and volatiles) still has sufficient materials to build a single small Kalpana style habitat for 8,000 colonists plus a dozen 5 gigawatt SPSs. Thus 120 meters is the smallest asteroid worthy of (first) capture, since it is barely large enough to build a permanent habitat rotating at 3rpm for Earth-normal gravity and with adequate radiation and meteoroid shielding.

Another consideration is the V-infinity of the asteroid, because slower asteroids are easier to move a distance large enough to make a significant difference in the slingshot.

The potential magnitude of a gravity assist is also constrained by how close to the center of the Earth the asteroid passes. Also, for a rubble pile we don't want to pass closer than the Roche limit or the asteroid may be torn apart by tidal effects, much as Jupiter's tide tore the comet Shoemaker-Levy into 20 fragments. The actual Roche limit depends upon density, but is likely to be of the order of 20,000 kilometers for a rubble pile asteroid passing near the Earth, and perhaps 5,000 kilometers for the Moon.

One might think that the composition of an asteroid would be the number 1 criteria, but in reality most asteroids should be quite valuable. A common carbonaceous chondrite might contain 25% nickel-iron mostly in the form of metal grains, 10% water, and several percent carbon plus everything else needed for life in space. But even a lowly LL chondrite will work.

The last consideration is the opportunity for intercept missions. We need to modify an asteroid's orbit when it is easy, some months or years before the targeted close approach. This is difficult for a high-inclination or long-period asteroid because it might only approach closely enough to the Earth for low-delta-V intercept missions once every ten or a hundred years. But an asteroid with a two-year period might present suitable launch windows every two years. Also, for asteroids with periods close to a year and with low inclinations, there may be two launch windows per year as the asteroid passes inside and then outside the Earth's orbit.

Some Possible Candidates

ASTEROID	MASS Megatons	Vinfinity Km/s	Period years	Approach Er	Approach Date
APOPHIS	27	5.87	0.89	4.6	13-APR-2029
2001 WN5	646	10.1	2.24	36	26-JUN-2028
2005 YU55	87	13.6	1.22	48	08-NOV-2011
1999 AN10	1360	26.24	1.76	61	07-AUG-2027
2009 WM1	14.5	14.2	1.28	108	23-NOV-2059
1999 RQ36	180	6.23	1.20	117	23-SEP-2060

From neo.jpl.nasa.gov
NEO Close Approach database

This table presents some possible candidates as of 25-APR-2011, all brighter than 24^{th} magnitude and expected to pass within 120 Earth radii in the next 50 years. Some of these may be eliminated by further refinement of their orbital parameters, while others can likely be added as new asteroids are discovered, or as orbits are corrected for known ones.
The entries on this table were gleaned from the Near Earth Object Close Approach database. The various tables, databases, and lists at the NASA web site are inconsistent, sometimes even on the same page. For example, the orbit visualization tool often has significantly different closest approaches than the "close approach" data on the same page.

A side note: Many asteroids have only been observed over a few days, resulting in large uncertainties in their orbital and physical parameters. The shapes, diameters, and masses of most asteroids are estimated, not known. Diameters are estimated from an asteroid's brightness and distance. But we can't measure the actual albedo, and observations at multiple wavelengths are used to judge the asteroid class, and from that estimate a typical reflectivity, and from that a formula results in an estimate of the diameter, and assuming an average density, we calculate the mass. This process has extremely large error bars. In April of 2010, radar imaging resolved the asteroid YU55. Previous estimates were that its diameter was 140 meters and its mass 4Mt. The actual measurement revealed a diameter of 400 meters and an estimated mass of 87Mt, a 22 fold mass increase.

Let's consider these asteroids:

Apophis is fairly well characterized, although it may not actually be an LL chondrite, and may therefore have a different albedo, diameter, and mass. As a candidate for Earth-orbit capture, it has the advantages of passing quite close and relatively slowly, plus launch windows occur in Aprils and Octobers near close approaches, suitable for a 1, 1.5, 2, or 2.5 year mission.

2001 WN5 is a bit on the large side, but it may pass about halfway between the Earth and Moon in 2028 which offers an opportunity to adjust its subsequent Earth approaches in 2037 and 2046. But being more than 20 times as large as Apophis means a lot of fuel is required, so 2001 WN5 will have to wait for a later, poorer opportunity, probably with a robotic mission.

2005 YU55 is three times as massive as Apophis, and approaches Earth, Venus, and Mars, giving multiple possibilities for gravity assists. Next year it will pass about 20% closer than the Moon's orbit, but it won't be that close again for quite a while. It makes frequent approaches, about every 11 years, with relatively close approaches in April of 2021, 2032, 2043 (etc), and in November of 2022, 2033, 2044 (etc). We can likely tune one close approach to allow a closer approach 11 years later that can lead to a capture 11 years after that.

1999 AN10 is a large, fast, and dangerous asteroid which will pass about as close as the Moon in 2027. It is large enough to build 7,500 5-Gigawatt Solar Power Satellites, or to house 2 million people in a 2 mile diameter habitat. Actually, we can solve Earth's energy problem for the next thousand years AND build a habitat for one million people, with materials to spare. While it is difficult to capture, it should be worth the effort.

2009 WM1 is only half the size of Apophis, and should be easy to capture some fifty years from now.

Lastly, **1999 RQ36** is 7 times the size of Apophis and passes 1.2 Lunar distances from the Earth in 2060. It, too, won't be easy to capture, but is also worth the effort.

It is likely that every one of these asteroids were placed into their current orbits by a slingshot around the Earth, a fact clear at a glance at the orbital simulation on the NASA web site. One of the principles of orbital mechanics is that an orbiting body (in a 2-body system) will always return to the altitude and velocity vector of its last orbit change. Ignoring hyperbolic orbits, one near Earth pass means more, until the body collides with the Earth or is deflected away by another planet.

ASTEROID CAPTURE COMPLICATIONS

But it seems that nothing is ever simple. Part of the problem is that we don't really know much about asteroids. Many of them appear to be rubble piles, and in some cases these spin so rapidly that their shape is constrained by their spin, yielding flying-saucer shapes. Others are contact binaries which might be exceptionally awkward to manipulate. We have more options with solid bodies, but we can't plan on that.

So how do we apply thrust? Two ways come to mind: dock and push, or use a gravity tractor to pull. Gravity tractors can only apply tiny amounts of thrust, but that might work, especially on longer missions. It would also help to dangle heavier components such as nuclear reactors and fuel as close as possible to the asteroid, with the thrusters some distance away so they can aim off to the side without much loss of thrust efficiency. But a 1,700 ton mass dangling 170 meters from the center of Apophis would be needed to apply the necessary delta-V over a 10 month period. Gravity tractors generally require very long missions.

We can dock with an asteroid and push against it in a traditional way, but there are complications due to microgravity and asteroid rotation. It is possible that a number of cables could be looped around the asteroid to hold the tugship securely in place. Even then, a spinning asteroid means that thrust can only be applied during a fraction of each rotation, wasting thrust and fuel to the extent that the applied thrust isn't directed in the correct vector.

EXAMPLE ASTEROID: 999042 APOPHIS

The asteroid Apophis will approach Earth to within 30,000 kilometers on April 13, 2029, significantly inside the orbits of our geostationary satellites. If we do nothing, the Earth's gravity will slingshot Apophis into a new orbit as it deflects it by about 28 degrees and boosts its velocity by 3.04 km/s. The result of this is that Apophis changes from a 0.89 year period Aten class asteroid orbiting mostly inside the Earth's orbit to an Apollo class asteroid with a 1.167 year period and an orbit mostly outside of the Earth's. I should point out that we don't yet know with any degree of certainty exactly what the resulting orbit will be, because tiny changes in the position of closest approach have a huge impact on the resulting orbit. The period given here corresponds to the keyhole that targets an Earth impact in 2036.

Delaying Apophis' arrival at the Earth's orbit by changing its velocity by only 10 cm/s results in a 1.5 km/s reduction in delta-V - a velocity gain of a factor of 15,000. I chose that particular slingshot because it results in a semi-major axis of 1 au, with a period of 1 year.

The Tisserand criterion indicates that it's possible to change Apophis' eccentricity to zero at the same time, although that would result in an inclination of about 10.5 degrees, and requires a much larger delta-V. In any case, what we really want is not a near-Earth orbit, but rather a subsequent slingshot around the Moon to remove excess velocity and drop the asteroid into Earth orbit. That may require some finesse and multiple slingshots, but it can be done. Look at the success of Cassini, Messenger, other missions that have relied on gravity assist slingshots to achieve what once was considered impossible for our current technology.

NEEDED TOOL: A TUGSHIP

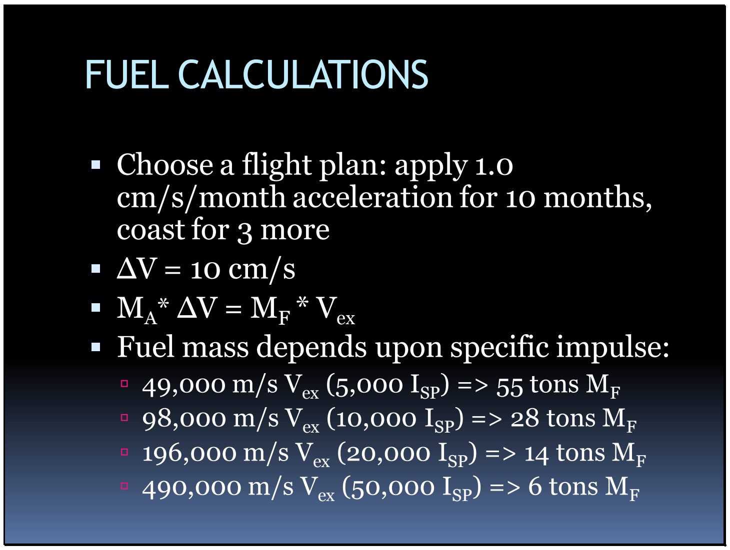
We still need to give Apophis that 10 cm/s nudge. Abrupt changes from nuclear bombs or high-velocity impacts are a bad idea for this type of mission, partly because we need finesse to fine-tune the orbit, and that's best done by the equivalent of titration. We need a tugship, a long-duration-mission, highly fuel-efficient spacecraft to gradually move the asteroid into a new orbit.

Magnetoplasmadynamic or VASIMR thrusters are likely the best choice to apply delta-V, as their high exhaust velocities reduce the total fuel mass needed, they can generate significant levels of thrust, and they should be able to achieve sufficiently high reliability.

Of course, we need to push or pull the asteroid, which isn't simple, partly because they are rotating, undoubtedly along an inconvenient axis. And they have enormous angular momentum which we can't easily cancel. This means we'll either have to dock – not land – at an appropriate location and thrust a fraction of the time, or use a gravity or magnetic tractor approach which might limit us to lower thrusts and longer missions.

Note that ion thrusters take copious amounts of energy. 25 megawatts can be generated by a 300 by 300 meter solar array, or by a single compact nuclear module available commercially. We do have a lot of experience with high-power nuclear modules in submarines and aircraft carriers, so that's an option I personally lean toward, but politics may dictate a less proven approach. Also, working fluids, cooling grids, and leaks need to be addressed for nuclear or for solar dynamic electric generation.

Given an appropriate power supply, we still need enough time and fuel to move an asteroid. So how much do we need?



From our mission-time-derived flight plan, we compute the needed delta-V. Conservation of momentum allows us to compute the needed momentum change and the product of fuel mass times exhaust velocity. The asteroid's mass is a given, but we can choose to some extent our mission time, and thus the needed delta-V. Double the mission time, halve the delta-V.

Note that doubling the exhaust velocity quadruples the needed energy (100 times the energy is needed for 10x velocity for a given amount of fuel). But doubling V_{ex} also halves the fuel mass required, so the net effect is doubling the required power for a given thrust duration. At a specific impulse of 5000, consuming 55 tons of fuel over a 10 month period requires 5 megawatts of continuous power.

With a lot of energy, we don't need much fuel at all. These numbers are all well within our technological capabilities. Of course, additional fuel will be needed to deliver the tugship and its load of fuel to the asteroid, but again, the numbers are within our capabilities. We can do this.

However, remember that Apophis is rotating and we may only be able to apply thrust half of the time. This doubles the thrust and power required.

MISSION OVERVIEW & TIMELINE

The proposed mission has two main phases and a three-year (or so) timeframe.

The first phase is to launch the necessary components and assemble them in orbit, some time in 2027.

The actual deep-space phase begins with a lunar slingshot for intercept injection in October of 2027, and docking with Apophis 5 months later. This requires 3 km/s of delta-V, and about 15 tons of fuel at an I_{SP} of 5000.

We would grapple Apophis, and apply 400 Newtons of thrust (enough to deliver 1.0 cm/s/month of acceleration) for half of every 30-hour day. Ten months of thrust consumes 55 tons of fuel. Then there is a three-month coast until the slingshot.

The major slingshot must occur on April 13, 2029. The goal is to change Apophis' orbit to achieve a lunar slingshot 1 year later to capture the asteroid into Earth orbit. Note that the initial thrust moves Apophis further from the Earth, and the subsequent lunar slingshot is necessarily even further out.

THE TUGSHIP

It must support an extended deep-space mission, providing everything the crew needs to thrive. The supplies estimate assumes ammonia provides hydrogen for carbon dioxide recycling, and most food is dehydrated. With efficient recycling of water and CO2, a 900 day mission for a crew of four requires 6 tons of supplies, plus a similar amount of equipment to recycle the water and oxygen, dumping methane overboard.

This mission plan requires 55 tons of fuel to change the asteroid's orbit, plus 15 tons for the intercept and docking, plus the initial spiral out and spiral down (as much as 20 tons), plus contingencies. I'd suggest at least 100 tons total, perhaps more. Note that if properly oriented, the fuel can provide significant radiation shielding during the trip to Apophis, and the asteroid itself provides even more, especially if the crew quarters can be partially buried.

We need to apply 200 newtons of thrust continuously for 10 months, or double that for half of the time. We'd need to double the power as well, 10 megawatts total. A 200 meter square array of 25% efficient solar cells generates 12 megawatts, the extra needed since ion thrusters aren't 100% efficient.

Lastly, we need some way to grab hold of the rotating asteroid. One possible solution is to launch 6 harpoons with 1-km lines around Apophis, retrieve the ends and securely tie them to the tugship. This would function as an effective net, and friction applies sufficient traction to apply thrust even at high angles of attack. We could break several of the lines and still hold on. Note that this is a good example of where people can easily accomplish a task which might be nearly impossible for an automated system.

IN-ORBIT TUGSHIP ASSEMBLY

This project plan assumes a separate launch of a construction shack housing and supporting six or more workers for several months, followed by launch of the assembly work force. A more efficient approach is possible, but requires man-rated super-heavy-lift launch vehicles.

The assembly crew integrates the tugship components (50 tons per launch):

- Two launches for the solar panels and supporting structures – total 100 tons
    - 1600 solar panels massing 60 tons
    - 40 tons of support structures
- Two launches for the fuel and thruster assemblies – another 100 tons
- One launch for the tugship core (crew quarters, tools, and supplies)

The total assembly time is 12-18 person-months, assuming extensive use of modular components.

Other launches include:

- The construction shack, tools, & supplies
- The assembly crew (man rated): 6 or more workers
- The mission crew (man rated, launched last to minimize the already long mission time): 4 to 6 astronauts

The number of people in each is an estimate, of course. While 6 workers may suffice to assemble the tugship during a two month project, double the people would simplify training, ease workloads, and provide significant redundancy.

Likewise with the deep-space mission crew. Two people may be able to handle the workload, but that is cutting it close. Four is a more likely minimum, and six is better.

NEXT STEPS

Continued research tops the list of the several logical next steps we should take. NASA is ideally suited for several of these, and the continuing search for potentially hazardous objects identifies the same candidate asteroids as a search for potentially capturable ones. A detailed analysis of potential slingshots should also be performed, as this analysis and mission plan was done using 2-body methods, patched conics, and simple momentum and energy computations. Another topic for detailed research is technologies for long-term missions, primarily recycling of water and oxygen with contaminant removal.

We do need to address several legal issues, which pose a serious problem for Western civilization private enterprise. Key among this is the right to own and exploit objects in space. If a person or company does not have the right to exploit space-based resources, they can have no incentive to acquire them, and the future of humanity in space is effectively dead.

We must also address the liability of moving asteroids. Certainly this should be done with the utmost care and intense oversight tempered with some sense of practicality. For example, the adjustment to Apophis orbit that I propose appears to pass through the 2036 impact keyhole. Does that mean we must move the orbit out and around that keyhole, or simply that we use reliable, even redundant systems, and closely monitor to track the potential need for additional intervention? I'm afraid that science and logic may have little to do with the outcome of that discussion. Also, some people will argue against any asteroid orbit modifications, and may use last minute legal maneuvers to cause critical launch windows to be missed.

We need to design and build a tugship using thruster and power technologies available in an appropriate timeframe. Of course, that research is an excellent task for Marshall Space Flight Center. The biggest challenge here might be in supporting deep-space, long-term missions with the human crews necessary to get the job done in the face of tight timeframes, complex systems, and unforeseen circumstances.

CONCLUSION

The bottom line is that we CAN capture asteroids into Earth orbit, thanks to the amplification of delta-V due to gravitational slingshots.

There are several candidate asteroids today, and there will be more tomorrow. There may be additional opportunities where the asteroid close approach is to Venus or Mars, although longer missions would be required.

The most important consideration is that capturing an asteroid such as Apophis places millions of tons of raw materials into Earth orbit where we need them to build solar power satellites, permanent orbiting habitats, and to advance humanity's exploration and further exploitation of the vast resources of space.

Lastly, we should never forget that capturing a potentially hazardous asteroid converts a dangerous threat into a resource of immense value.