The Case for Ballast

Abstract
"The Case for Ballast" describes how ballast is a fundamental unifying principle that connects the dots between many past and future missions; the Asteroid Retrieval Vehicle should be designed to allow for obtuse thrust; physical equations are included to calculate the ballast mass to use an ARV as a planetary defense system.

Primary Response Area: 2
2. Asteroid Redirection Systems; 2c. Refinements of the Asteroid Redirect Mission;
3. Asteroid Deflection Demonstration; 3b: "gravity tractor"; 3c: planetary defense;
4. Asteroid Capture Systems: systems to de-spin an asteroid;
6. Partnerships and Participatory Engagement: commercial and national profit.

This response to the **ASTEROID INITIATIVE REQUEST FOR INFORMATION** is submitted pursuant to, and by, the following:

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Posted Date:	Jun 18, 2013
FedBizOpps Posted Date:	Jun 18, 2013
Recovery and Reinvestment Act Action:	No
Original Response Date:	Jul 18, 2013
Current Response Date:	Jul 18, 2013
Classification Code:	A -- Research and Development
NAICS Code:	336414

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System Concept: The Case for Ballast

Ballast is simply anything heavy that may be placed low in a vessel. In water, ballast lowers the center of gravity of a ship, which improves its stability and control. Ballast adjusts a ship's draft and compensates for load. Ballast is usually inert and dense.

Ballast occupies both our past and our future. Sailors have been putting ballast in their boats since ancient times. Vikings used to place a layer of rocks low in their ships near where the mast met the keel. Tall ships often use gravel for their ballast to steady the ship against the wind. Ballast is carried aloft to control buoyancy as sand in hot air balloons and as water in airships. Our largest and most modern ships still use lowly ballast, held in dedicated ballast tanks, to steady their way. Apollo 13 used ballast to trim the command module's center of gravity for reentry.

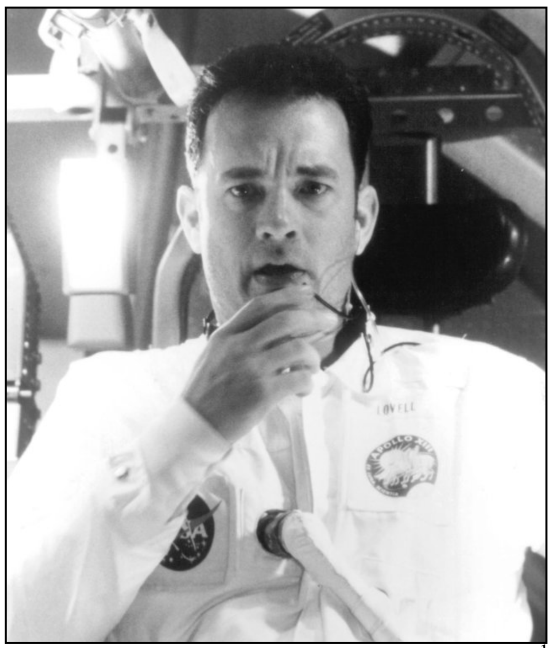


Fig. 1. "Uh, say again, Houston? Ballast?"[1]

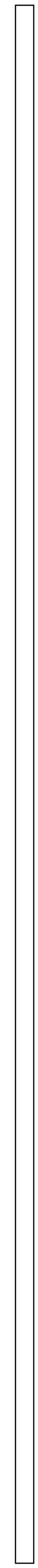
Ballast means mass added to a spacecraft after its initial launch from Earth that is stowed mechanically onboard.

This narrow definition of ballast helps to focus our attention towards asteroids. Ballast excludes all of the initial mass of the spacecraft, including its structure, occupants, computer, engines, propellant, fuel, and all inert mass at launch. Ballast broadly includes any kind of added mass, such as cargo, consumables, and inert mass of all sizes, from dust to boulders. However, an asteroid that is too large to mechanically stow onboard the spacecraft is not considered ballast, even if the spacecraft lands on it.

Ballast connects the dots between the Asteroid Retrieval Vehicle (ARV), the gravity tug, planetary defense, asteroid mining, human interplanetary spaceflight, and even starships.

Gravity Tug Thrust Equals Weight

The quickest gravity tug will use half of an asteroid as ballast to pull the other half, holding the ballast in the "bottom" of the craft.



Proof:
A gravity tug is a craft (C) that is gravitationally coupled to an asteroid (A), and may be laden with some ballast (B), which is mass that was gathered from the asteroid.

The average thrust of a gravity tug equals the weight of the laden craft, relative to the remainder of the asteroid. If the laden craft's thrust is less than its weight, it will fall, but if more, it will escape. Gravity limits average thrust.

The gravitational force between the asteroid (A) and the craft (C) equals $\overrightarrow{f_{AC}}$,

$$\overrightarrow{f_{AC}} = \left(\frac{G}{(\overrightarrow{r_{\overline{AB}}} - \overrightarrow{r_{\overline{BC}}})^2} \right) (m_A - m_B)(m_C + m_B)$$

where $\overrightarrow{r_{\overline{AB}}}$ and $\overrightarrow{r_{\overline{BC}}}$ are the centers of mass of the asteroid minus ballast, and of the craft plus ballast. The masses of the asteroid, ballast, and craft are m_A, m_B, and m_C.

Weight is maximized when the mass product is maximized, and the distance between is minimized.

Even kids know that if you have a long skinny rectangle,
then you can increase the area of the rectangle without changing its perimeter by taking away some of the long side and adding it to the short side. The perimeter is like the mass, and the area is like gravity. The long side is the asteroid, the short side is the craft, and the adjustment is the ballast.

If we consider rectangles with sides of length $(m_A - m_B)$ and $(m_C + m_B)$, they will have the most area when their sides are equal, which is when $(m_A - m_B) = (m_C + m_B)$. But the asteroid mass is so huge relative to the craft, that we can ignore the craft's tiny mass to estimate that $m_A \approx 2m_B$. In other words, the optimal ballast mass is one-half of the asteroid's total mass. Even a little ballast helps a lot!

The optimal distance $(\overrightarrow{r_{\overline{AB}}} - \overrightarrow{r_{\overline{BC}}})$ between the asteroid and the laden craft is simply a matter of physical geometry. The craft should simply fly as close as possible without touching.

Gravity Tug Geometry

The optimal shape of the laden craft would have the center of mass as close as possible to the asteroid, which is in the "bottom" of the craft, right where every other sailor places their ballast, where "down" is defined by the gravity gradient.

A gravity tug's thrusters cannot easily be placed directly on the central axis of thrust, as is customary in most rocket designs, because the asteroid is in the way. Gravity always pulls, thrusters always push, the exhaust must not impinge on the asteroid, and the best place to hold ballast is as close as possible to the asteroid.

This informs the nominal gravity tug geometry, as in Figure 2, where multiple thrusters pull the load mass, instead of push it.

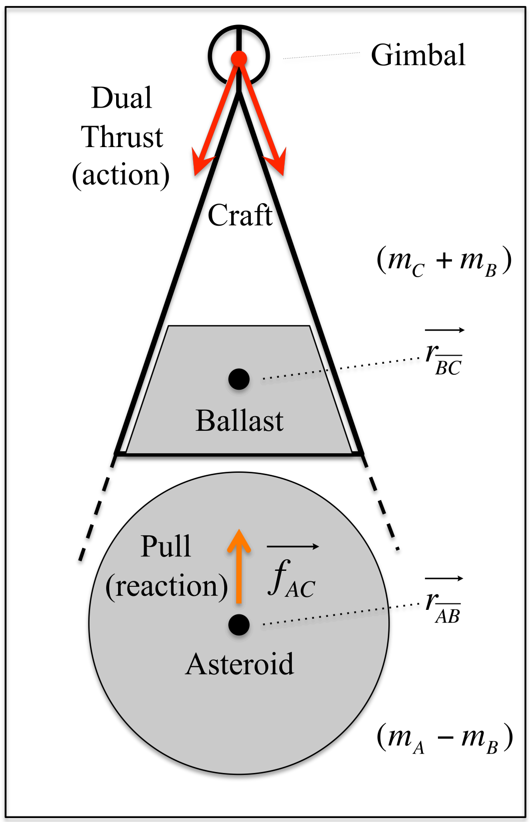


Figure 2. Gravity Tug Maneuver

In Figure 2, two thrusters are used to balance the torque about the point $\overrightarrow{r_{BC}}$, but this could also be achieved with a single thruster, spin-stabilized about the central axis.

It is necessary for a gravity tug to apply thrust on an angle, φ, so that the engine exhaust does not impinge on the asteroid. The thrust is applied along an imaginary thrust exclusion cone around the asteroid.

Asteroid Redirect Mission

The Asteroid Redirect Mission should be the first in a series of missions. It should demonstrate two additional maneuvers, using spin-stabilized obtuse thrust.

The first Asteroid Retrieval Vehicle (ARV) will be a laden craft. The ARV is not required to perform in the gravity tug role to accomplish the Asteroid Redirect Mission. However, we can use the Gravity Tug Geometry to better understand the design.

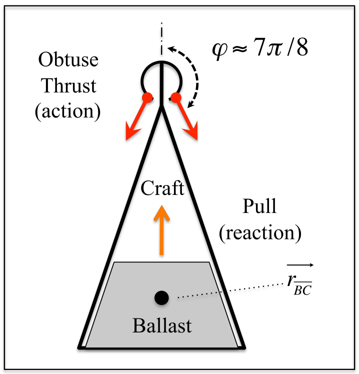


Figure 3. Obtuse Thrust

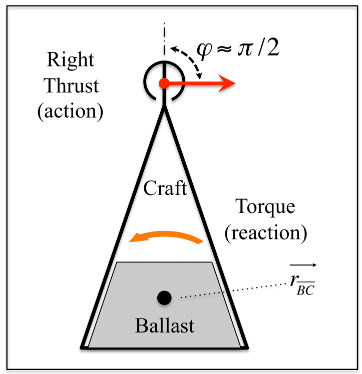


Figure 4. Right Thrust

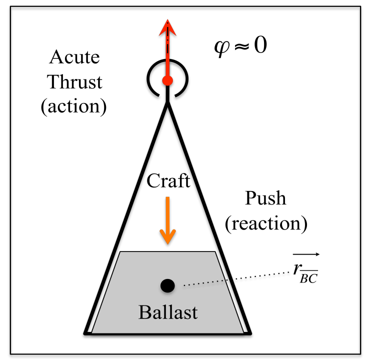


Figure 5. Acute Thrust

Obtuse Thrust: Pull
During the ballast capture maneuver, the ARV must slow its approach to the ballast, especially if the ballast is being picked up off the surface of a larger asteroid.

Obtuse thrust, figure 3, is a critical design element for all gravity tugs. A gravity tug maneuver applies obtuse thrust to maintain a continuous hover over an asteroid. It would be helpful to gain some experience with obtuse thrust on the first mission.

The thrusters may also be mounted on the vehicle waist rather than the nose, just as long as their thrust does not impinge on the imaginary thrust exclusion cone around the load. The torque must be balanced, using either two thrusters or spin stabilization.

Right Thrust: Torque
After capturing the ballast, the ARV must fully de-spin it. One way to do this is to apply right thrust, figure 4, by moving the thruster to a ***right angle*** to apply torque to the load.

Acute Thrust: Push
After stowing the ballast mechanically and de-spinning the load, the ARV is free to apply acute thrust, figure 5, just as any other gimbaled inline rocket would.

The Asteroid Retrieval Vehicle (ARV) should be changed so that:
1. The ARV can apply obtuse thrust.
2. Demonstrate a gravity tug hover maneuver with no ballast.
3. Demonstrate a spin-stabilized obtuse thrust maneuver while laden with ballast.

Gravity Tug Demonstration Mission

The Gravity Tug Demonstration Mission should follow the Asteroid Redirect Mission.

The B612 foundation has already used a computer to simulate a gravity tug hovering over an asteroid[2]. That result showed that a gravity tug could successfully redirect an asteroid, given enough time. However, the B612 simulation avoided physical contact with the asteroid. Only the mass of the craft was used to demonstrate the simulated hover.

A lightweight hover is like a barn swallow, *Hirundo rustica,* hovering over a cat. But can a laden swallow[3] hover over a cat while carrying a coconut? That's more difficult. The gravity tug demonstration mission would show that a laden craft can hover over an asteroid, using twin SEP rockets as propulsion, and Xenon as the reaction mass.

The Gravity Tug Demonstration Mission should be changed so that:

1. The craft is laden with some ballast mass from the asteroid that it will tow.
2. It uses substantially the same ARV design that was previously flown.
3. It demonstrates dual SEP thrusters.

Asteroid Mining Demonstration Mission

The Asteroid Mining Demonstration Mission should follow the Gravity Tug Demonstration Mission.

Even with the very high specific impulse, Xenon fuel tanks might not be able to carry enough mass to save the planet. For all rockets, the velocity change depends on the fraction of mass lost. Launching mass from Earth is very expensive.

Use some of the asteroid to move the rest of the asteroid!!!

Chondrulic Rockets are propulsion systems that use mass obtained from an asteroid as propellant mass to develop rocket thrust. I discuss them at length in a separate RFI.[4]

The Asteroid Mining Demonstration Mission would use the same ARV, with SEP thrusters and Xenon fuel, to rendezvous with a medium-sized asteroid. The ARV or a daughter craft would extract some chondrules from it to use as propellant, and the ARV would mechanically stow that mass as ballast.

The ARV would then use new chondrulic rockets as primary thrusters. It would direct obtuse thrust around the asteroid to hover over it. When the propellant is nearly exhausted, it would reduce the chondrulic rocket thrust and land on the asteroid.

Solar powered chondrulic rockets enable asteroid mining because they can refuel, by picking up chondrules to use as reaction mass. In an extended mission, the ARV would take time to refuel, and then use chondrulic rockets to fly to a different asteroid, demonstrating an unlimited capability to hop between asteroids.

Planetary Defense Emergency Mission: SOLVED

If a large asteroid were on a collision course with Earth, could we prevent the impact? This question is the rocket fuel for our imagination, and our answer could demonstrate that we are indeed smarter than the dinosaurs. This is the grand challenge.

Ballast can increase thrust a thousand times! For a gravity tug, thrust equals weight so increased thrust ***requires*** ballast. Ballast can increase weight by several orders of magnitude, which is why a gravity tug laden with ballast can save the world.

A chondrulic rocket can hover over an asteroid even if it has a low specific impulse. Chondrulic rockets tend to consume a significant mass fraction of the asteroid. A larger mass fraction, accelerated by a low to moderate specific impulse chondrulic rocket, means a larger change in velocity and much less energy consumption.

High specific impulse rockets are not required to achieve planetary defense. High specific impulse rockets produce safer exhaust because they tend to eject smaller particles, such as dust. They consume a lot more energy, and can easily exceed the energy budget, because kinetic energy varies by the square of the exhaust velocity.

QUESTION: Suppose an asteroid (A) was headed on a collision course with Earth. To save the world, we launch a craft (C) on a mission to gather some ballast (B) from the asteroid to increase its weight, with a daughter craft (D) that lands on the asteroid to gather dust suitable for use in the chondrulic rockets. Are we smarter than the dinosaurs?

ANSWER: YES! Here is how to design a gravity tug to can save Earth.

The masses of the Asteroid, Ballast, Craft, and Daughter are $m_A, m_B, m_C, and\ m_D$. The radius of the asteroid's tallest mountain is r_A. The flight safety radius of the laden craft is r_C from its revised center of mass. The craft uses chondrulic rockets to eject chondrules with velocity u. The rockets are mounted on a tower, and thrust at an obtuse angle, φ.

Upon arrival, the daughter craft lands on the asteroid, collects chondrules, and maintains the flow of chondrules so as to keep the weight of the laden craft constant.

The gravitational force between the Asteroid and the Craft $\vec{f}_{AC}$ equals the weight of the laden craft over the Asteroid minus ballast. To hover over the asteroid, the cosine component of the total thrust must equal the weight of the laden craft.

$$\vec{f}_{AC} = \frac{G(m_A - m_B + m_D)(m_B + m_C - m_D)}{(r_A + r_C)^2} = ((m_A + m_C)\frac{dv}{dt} - u\frac{dm}{dt})\cos(\varphi + \pi)$$

The effective thrust velocity is diminished by the cosine of the thrust angle. Since this rocket "pulls", φ is obtuse, so we add π to the thrust angle to change the sign (±).

$$v_e = u\cos(\varphi + \pi) = -u\cos(\varphi); \quad I_{SP} = v_e / g_0$$

Since the gravity tug craft is hovering, and the asteroid is accelerating very little, we consider the thrust cosine in the limit as $\frac{dv}{dt} \to 0$ to find the mass flow rate, $\frac{dm}{dt}$. The total mass flow includes both sine and cosine components. The energy required accumulates over time as the mass acquires kinetic energy from the chondrulic rockets.

$$\vec{f}_{AC} = -u\frac{dm}{dt}\cos(\varphi+\pi) = u\frac{dm}{dt}\cos(\varphi); \quad E_k(t) = \tfrac{1}{2}(\frac{dm}{dt}t)u^2;$$
$$\frac{dm}{dt} = \frac{-\vec{f}_{AC}}{u(\cos(\varphi)+\sin(\varphi))} = \frac{-G(m_A - m_B + m_D)(m_B + m_C - m_D)}{u(r_A + r_C)^2}$$

If the ballast is maintained so that the weight is constant, then the thrust is constant, and the mass flow rate is constant, so that the mass of the system decreases linearly with time. The asteroid's velocity changes over time according to the Tsiolkovsky rocket equation:

$$\Delta\vec{v}(t) = -u\cos(\varphi)\ln(\frac{m_A - \frac{dm}{dt}t + m_C}{m_A + m_C});$$
$$\Delta\vec{v}(t) = -u\cos(\varphi)\ln(\frac{m_A + m_C - (\frac{G(m_A - m_B + m_C)(m_B + m_C - m_D)}{u(r_A + r_C)^2})t}{m_A + m_C})$$

How many parameters can our engineers adjust? The asteroid's mass and shape constrain the optimum hover height and thrust angle. The masses of the craft and daughter are constrained because they must launch from Earth. Since thrust equals weight, high specific impulse rockets do not increase thrust, but merely reduce the exhaust hazard by reducing the mass flow rate. There is nothing left to adjust, except for the ballast mass.

Ballast is the only adjustable parameter!

Once the size, mass, duration and $\Delta\vec{v}$ are known, we can just plug those variables in to the velocity function above, and examine the family of $\Delta\vec{v}(t)$ curves traced out as the ballast mass varies in the range $0 \le m_B \le \frac{1}{2}m_A$.

Hopefully we will find a portion of the curve where the velocity can be changed quickly enough to save the Earth. However, if the required $\Delta\vec{v}(t)$ cannot be found in the range $0 \le m_B \le \frac{1}{2}m_A$, then *no such gravity tug could possibly save the Earth.*

In that case, engineers should invent a different way to connect the rocket to the asteroid, such as a rope, and increase the mass flow rate into the chondrulic rockets.

Human Spaceflight Missions

NASA already sees that the Asteroid Redirect Mission is a "Stepping-Stone to Mars". Ballast makes this statement literally true.

Suppose in the future, the Asteroid Redirect Mission had successfully placed a small asteroid in a deep retrograde lunar orbit, and a crew from the Earth had visited it and completed their science mission.

How could we make use of that rubble pile? On the way to Mars, we could use the rubble as radiation shielding for humans, and as reaction mass for chondrulic rockets.

Rubble placed in the outer hull of an interplanetary craft could provide some protection from the harmful radiation outside. It would be far too expensive to launch that much shielding mass from Earth. However, we could instead launch the craft from Earth into that same deep retrograde lunar orbit, and rendezvous with the retrieved asteroid. The craft could then load the ballast into shielding tanks before the humans arrive for their gravity-assisted flight to Mars.

Naturally, that increased mass would require more fuel. Again, it would be far too expensive to launch that much chemical propellant from Earth. Even if the asteroid contained water, we would not want to electrolyze and subsequently jettison all that valuable water as propellant.

We might look towards electric propulsion using Xenon gas. Although this kind of rocket has an extremely high specific impulse, the large mass of the ballast would require a very large quantity of Xenon gas, which is not easily replenished.

Another option is to invent a new kind of rocket, the electric chondrulic rocket, specifically designed to eject asteroid dust at a high speed. Someday, in the far distant future, we may even develop a nuclear electric chondrulic rocket with velocities a significant fraction of the speed of light.

Since the reaction mass can be replenished from an asteroid, the craft might even refuel for a round trip. Someday it might be an asteroid orbiting a distant star, but to get there, we know that energy will be the main problem; mass should be relatively easy to find.

Maturity (Technology Readiness Level)

Ballast is as ancient and eternal as mass itself. Inertia is always ready.

However, our technology for gathering ballast from an asteroid, to stow it aboard a spacecraft, and to use asteroid mass as rocket fuel is very immature. We must continue our experiments with ballast, continue to learn from the results, and continue to design new technology to meet the challenge.

Development approach: Steady Incremental Growth Forever

Ballast is a fundamental unifying principle that will underlie future spaceflights to asteroids and anywhere beyond. Ballast connects the dots between the missions.

The Asteroid Redirect Mission lays the foundation for a series of missions because it is the first mission that conducts a major experiment with ballast. A related series of Asteroid Retrieval Vehicles can fulfill multiple roles.

Conclusion: *The Case for Ballast*

We explored how ballast is a fundamental unifying principle for space missions. Ballast connects the dots across time, from the deep past to the distant future.

Along the way, we learned the following lessons:

1. Refine the Asteroid Redirect Mission so that the Asteroid Retrieval Vehicle can provide obtuse thrust.

2. The average thrust of a gravity tug equals the weight of the laden craft in the asteroid's gravity field. A little ballast greatly increases average thrust.

3. The maximum possible average thrust for a gravity tug equals the weight of half of the asteroid, in the gravity field of the other half.

4. Ballast is the only adjustable parameter in a gravity tug mission because the physical character of the problem constrains all the other factors.

5. The Asteroid Retrieval Vehicle can be developed as a related series of spacecrafts, so that early missions build towards later ones.

6. Ballast will be an important consideration for all future asteroid missions, providing radiation shielding, and reaction mass that can be replenished.

References and Credits

(1) Tom Hanks as Jim Lovell, Apollo 13 mission commander, "Apollo 13" motion picture, Photo by Universal Pictures – © 1995, media obtained via imdb.com; phrase from script.

(2) B612 Foundation. Gravity Tug Computer Simulation, http://b612foundation.org/.

(3) Monty Python and the Holy Grail, Terry Gilliam, Terry Jones, Møøse, Python (Monty) Pictures, 1975.

(4) Rick DeWitt, "Chondrulic Rockets", a separate paper in this same RFI, response area 3, 2013.

Thank you NASA, for asking for my input.