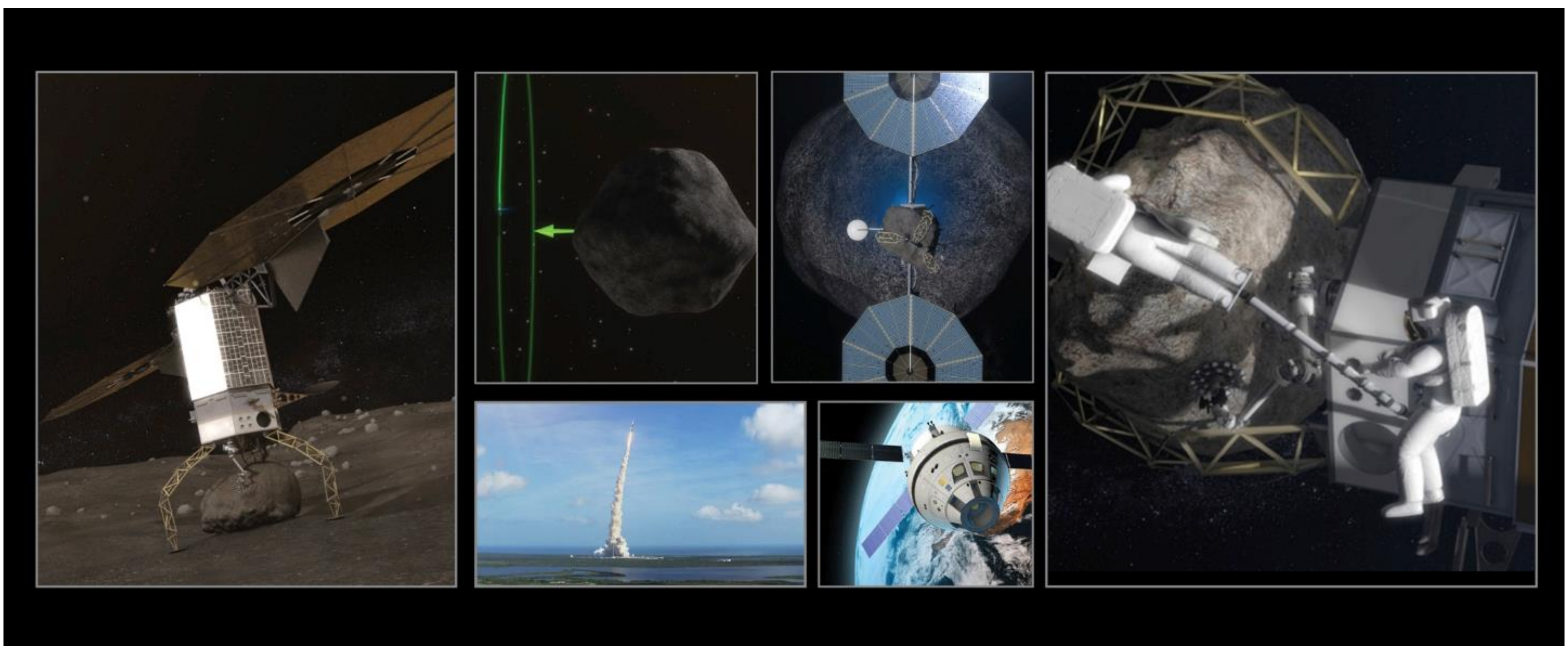
National Aeronautics and
Space Adminstration

Asteroid Redirect Mission (ARM)
Formulation Assessment and Support Team (FAST)
Final Report
Complete Public Comments



December 9, 2015

This document contains public comments received in response to the Asteroid Redirect Mission (ARM) Formulation Assessment and Support Team (FAST) Final Report prior to end of the public comment period on Dec. 4, 2015. Inputs that are relevant to the FAST Charter and in the scope of the mission formulation, as well as other inputs that were applicable to the ARM in general, but were not directly relevant to the FAST activity and report, are included in this document. The inputs are listed in the order that they were received. These inputs are provided in their entirety without any alteration to the text other than the removal of extra lines and any direct contact information that was provided (i.e., e-mail, telephone, and address), except when provided in accompanying attachments. Please note that all cited page numbers, figures, and tables refer to the draft report released on November 23, 2015.

This document and the FAST Charter can be found on the ARM FAST website: http://www.nasa.gov/feature/arm-fast.

Input from Marshall Eubanks (Asteroid Initiatives, Inc.)

To : Dan Mazanek,
NASA ARM Mission Investigator
NASA Langley Research Center

From : T. M. Eubanks
Asteroid Initiatives, LLC

Subject: Considerations for the Asteroid Redirect Mission (ARM) Formulation Assessment and Support Team (FAST)

Date: August 7, 2015

The FAST Call says that the FAST should provide initial inputs for potential investigations and payloads related to the Asteroid Redirect Robotic Mission (ARRM) and focused on the following four main areas:

- *Science*
- *Planetary Defense*
- *Asteroidal Resources and In-Situ Resource Utilization (ISRU)*
- *Capability/Technology Demonstration*

I think that it would be useful to give you my ideas on issues related to these 4 topics that the FAST either will have to or should deal with, and ideas and experience I could bring to the effort. I have tried to follow the progress of ARM, and I will not dwell on the areas I feel are under control *(although details of these may also require the attention of the FAST), either based on ARM presentations, or the Design Reference Mission of the OSIRIS-REx mission.*

I. Science

In Science, as you know I was a strong proponent of "Option B," and I was very pleased that it was selected. I also think that 2008 EV5 is an excellent candidate mission target. With these choices the ARRM and ARCM have a potential for providing ground-breaking science.

Various aspects of ARM science that I think need attention are are

1.) Asteroid Rotation and Dynamics. The rotation of the small asteroids (roughly, those with radii between 100 m and 10 km, which include all 4 of the present ARRM candidates) are thought to be strongly perturbed by radiation torques ("YORP"). These can bring these asteroids to the brink of rotational disruption, leading to the creation of an equatorial ridge from material flowing "down" from higher latitudes, with material from this ridge possibly being spun-off into orbit and forming satellites. Three of the four ARM candidates, including 2008 EV5 spin rapidly enough that they have presumably been subjected to significant YORP torquing, and seem to possess equatorial ridges indicating past episodes of mass shedding. As far as is known, however, none of the ARM candidates possess satellites. Other such bodies (for example, both Didymos and 1999 KW4) do have satellites that appear to have formed from rotational shedding of surface material from equatorial ridges; an open scientific question is whether the ARM targets had such satellites and lost them, or never formed them. A science goal for the ARRM should be to describe the YORP torque and rotation state of the target as accurately as possible during the initial "stand-off" phase of the mission (before the spacecraft itself can perturb the satellite's albedo or rotation.) This should include

• An accurate characterization of the regions important to YORP and Yarkovsky radiation pressure forces, enabling the estimation of thrusts in both the visual and IR, including the shape, orientation, location, albedos and reflection coefficients of reflecting and radiating regions on the target. It is crucial that this be done before the ARRM spacecraft disturbs the surface of the target. This can be done during the general stand-off examination planned for the ARM target, but the FAST needs to make the point that, beyond the characterization of candidate boulders to retrieval, the ARRM needs to conduct a global scale surface characterization for this and other scientific purposes (see below). Fortunately, I believe that this important scientific goal can be accomplished with planned instrumentation.

• The ARRM should attempt to determine the axial rotation as accurately as possible, and to bound or detect its change with time (as would be expected from YORP radiative torquing). With a limited time duration, previous ground-based or spacecraft -based observations are likely to be important for this goal.

• Non-equatorial torques or mass movements will excite polar motions as well as speed-ups or slow-downs of the axial rotation rate. These could derive from meteorite impacts, uneven surface mass-slumping to the equatorial ridges, internal mass motions or by YORP, or could even be remnants of an earlier stage of non-principal-axis rotation. The two roughly spherical ARRM candidates will have Eulerian wobble periods of the order of 50 - 100 hours (assuming no rigidity and a uniform density distribution); the actual polar motion periods for this bodies are likely to be somewhat longer. (Itokawa is not a fast rotator and is not approximately spherical; a body of its shape is likely to experience librations in all three axes from similar causes. Although the detailed dynamics will be

different, the principle of the desirability of an accurate characterization of the rotational dynamics will be the same.)

- *The ARRM should attempt to observe (or rule out) such polar motions, ideally at the centimeter level or better, during the initial 2 month characterization period. Asteroidal polar motions will certainly be excited by meteorite impacts, post impact shaking, mass slumping, possibly by YORP; once excited, the resulting polar motions are thought to take kilo-years to completely decay. This task will require the use of Lidar, and would benefit from the placement of retroreflectors to serve as geodetic markers; the goal should be to detect any motions at the centimeter level during the 2 months of asteroid characterization planned in the ARM mission profile. (The target may conceivably also exhibit significant variations in longitude; a measurement plan sufficient to observe cm level polar motions should also suffice to observe similar sized longitude variations during the characterization period.)*

- *The accurate characterization of the rotation state during the initial stand-off period would ideally be done with the LIDAR ranging from the ARRM spacecraft; landing of laser retroreflectors on the target by FlatSats to serve as geodetic reference points should be considered (see the discussion in Section IV, below).*

- *The observation of these rotational dynamics in a principle-axis rotating body would provide information on the moments of inertia (and thus the internal density distribution) of the target and on its past rotational history. Very similar dynamics will govern the much larger motions of non-principal axis rotators. ARM could thus provide information that would be valuable in understanding the dynamics of these bodies as well, which could be very important for planetary defense if a hazardous body was also a non-principle axis rotator.*

- *This effort should be repeated after the boulder is extracted, during (or just before) the gravity tractor planetary defense experiment. My calculations indicate that the direct rotations and accelerations imposed by the ARRM (even if multiple boulders are extracted before a suitable one is found) are not likely to be directly observable by ARRM lidar (i.e., they are likely to integrate to less than a mm over a several month period). However, the ARRM boulder retrieval could easily significantly change the albedo (IR and / or optical) of the target body sufficiently to significantly change the Yarkovsky thrust or YORP torque experienced by the target body. The ARRM must try to quantify these changes as*

- *Determining the direct gravity tractor thrust will require evaluating the Yarkovsky thrust on the body, and that may have changed from before the mission.*

- *Optical changes to hazardous bodies are a different means of asteroid deflection that has as yet received little attention (in effect, using Yarkovsky thrust as a engineering tool). The ARM could thus provide valuable information about the efficiency of this deflection method.*

2.) Causes of surface restructuring. The two smallest asteroids with high resolution spacecraft imagery, Toutatis and Itokawa, do not exhibit craters, while the larger and more massive asteroids with such imagery are saturated or nearly saturated with craters. (Many of the small asteroids imaged by radar also seem to lack surface craters.) It is thought that the smaller bodies are, after major impacts, subject to long term shaking, which could erase existing surface features (such as impact craters on the surface). The physics of this surface restructuring is unclear, and ARM may be able to provide important constraints on this process.

• *An accurate characterization of the shape of the target (again, before any disturbances by the ARRM) will characterize "fossil" mass motions due to rotational forcing or meteorite impacts. Ideally, this should be done with sufficient spectral resolution to characterize differences in space weathering and composition for different surface flow features.*

• *The disturbance of the surface by boulder collection will shake the target asteroid, and could cause mass flows. Flows resulting from such perturbations should be documented during and after collection period, which will help substantially in parameterizing mass flow models for meteorite impacts, tidal stresses and in response to attempts to redirect hazardous asteroids. It may even be possible to conduct actual surface restructuring experiments with the ARRM spacecraft, by shaking or prodding the asteroid's surface, say in a "sea" or "pond" type area (see below).*

3.) "Granular Physics" and the Causes of Regolith Cohesion.

The source of the cohesion exhibited by many small asteroids remains unclear. Some small asteroids rotate substantially faster than their rotational disruption periods, and so must have internal cohesion. However, even the small asteroids that do not exhibit cratering also must have internal cohesion (as otherwise it is hard to see why shaking or mass flows simply do not disrupt the body entirely). Likewise, the flow of material into an equatorial ridge is hard to understand purely under gravity. The ARRM mission should offer numerous opportunities to investigate this issue in situ in a surface properties experiment, both during the boulder capture process and possibly during sampling or other surface operations. Investigating the causes of asteroid cohesion are important both for science, and for planetary defense, as the lack of surface cohesion will limit the acceleration that can be applied without disruption during the deflection of a hazardous body. Among the most important regions for an in situ surface properties experiment would be any smooth "seas" or "ponds" of smooth fine material (see the discussion in the next point).

• *Observations of surface restructuring during the boulder collection process itself should provide information on the cohesion between the boulder and the surrounding regolith. (Even if the boulder is simply resting on the surface, there still is likely to be some cohesion between it and the regolith.) Much of this data will probably be collected for engineering purposes, but it is important that it be analyzed and made available to the community.*

• *It is also important to observe the behavior of material shaken loose or dropped during the boulder acquisition process, and other surface motions caused by surface operations. van der Waals forces are entirely contact forces (they have effective ranges for most surfaces of 10 - 100 nanometers) while electrostatic and gravitational forces are, of course, long range, and will continue to influence motions even after surface components are separated. Care observations of the results of ARRM operations should serve to distinguish between these possibilities.*

• *The ARRM should map the surface slopes and local acceleration (gravitational plus rotational) for the complete surface of the target asteroid. I believe that the basics have been covered; however, I would like the FAST to consider landing picospacecraft with accelerometers to provide ground truth for this effort. (See Section IV, Capability/Technology Demonstration, below, for ideas on how this could be accomplished.)*

4.) Contextual Sampling of the Target Asteroid.

There are plans to do a contextual sampling of the regolith near the boulder capture. I applaud and fully support this effort, and realize that there are limits to how many contextual samples can be returned. However, I think it is important to realize that samples are badly needed of the "smooth" surfaces present on Itokawa and Eros, should such surfaces be present on the ARRM target. The highest resolution imagery from Hayabusa showed that the smooth "beach like" surfaces (for example, those forming the "Muses Sea") were actually very fine material, with sub-centimeter grain sizes, while the "ponds" of Eros exhibited even finer (unresolved) material. It is important for both science and planetary defense that this material, if present, is sampled by ARRM.

- *This material would never survive passage through the Earth's atmosphere to be sampled as meteorite material. Properly collected samples (which could be a fraction of a kilogram) would this provide a sample of a new type of material unavailable from meteorite samples.*

- *Two theories for the origin of this material are that it results from thermal fracturing or is impact ejecta. This would be straightforward to result through the examination of samples, and could even be done by astronauts during the ARCM.*

- *The sources of the cohesion exhibited by this fine material is unclear at present. Properly collected samples, stored in vacuum, would enable this mystery to be studied on Earth or in distant retrograde lunar orbit during the ARCM.*

- *In addition, both the Apollo Lunar experience and the needs of Asteroidal ISRU show the benefits of core samples, and I would like to urge that the ARM mission conduct at least one core sample, ideally from a sea or pond area, or failing that, from the vicinity of the collected boulder. Only core samples can determine the distribution of material with depth, and core samples would thus be essential in determining the circulation and size-sorting of the fine granular material, and (together with solar wind methods of dating surface exposure) also constrain the motion of this material over time and past resurfacing events. (In particular, it should be possible to distinguish between a slow circulation of material to and from the surface and episodic overturning or resurfacing of the body.)*

5.) Electrostatic levitation.

Electrostatic levitation of fine material is known to be important for the Moon and the rings of Saturn, and is thought to be a possibly important means of the lost of dust from asteroidal surfaces. This levitation is thought to be connected to charging from the solar radiation and solar wind, and thus to be strong near the night and day side terminator.

Levitated dust is thought to be important in removing very fine material from strong asteroids; the AARM mission could test this hypothesis and provide valuable observations for improved modeling of this phenomenon.

- *At the beginning of the mission, the spacecraft should attempt to observed levitated dust through forward or reversed scattering of light. (This would require long optical time exposures of the limb of the target asteroid.)*

- *A levitated dust sample return (which could be as simple as a container opened and then closed at the right orbital phase) would provide the first samples of such material from any solar system object.*

- *Even if levitated dust is not detected during the characterization period, it is highly likely to be present after dust is liberated by the disturbance of the surface during boulder collection. The ARRM mission should be able to describe the amount of levitated dust liberated by boulder capture, by observations of scattered light before and after the capture period, and also describe the loss rate of dust through observations conducted during the gravity tractor experiment.*

6.) Comparison with Ground Based Observations

- *As with any asteroid mission, an important scientific goal will be the comparison of in situ results with previous ground-based observations (this will be particularly true if the target is an object, such as 2008 EV5, which is not been previously visited by spacecraft). I would use the OSIRIS-REx DRM as a reference for this effort. Clearly, the actual observations (radar, optical and spacecraft) available for the particular target chosen should be carefully considered in planning this effort.*

II. PLANETARY DEFENSE

As I have indicated above, there are strong connections between many of the science goals and planetary defense. The description of the proportions and distribution of fine and coarse material, and of the nature of the cohesion between the various components making up the asteroid, will be very important if it is ever necessary to resort to kinetic impacts or nuclear explosions to deflect a hazardous asteroid.

During the ARRM "gravity tractor" planetary defense test, it will be important to have a very tight geodetic control over the target asteroid, and the ARRM spacecraft itself.

- *The ARRM spacecraft will not itself be a drag free platform, and it will thus be necessary to combine radiometric observations of the ARRM spacecraft from Earth, and LIDAR observations of the target asteroid from the ARRM spacecraft, to determine the asteroid's velocity change from the gravity tractor.*

- *The ARRM spacecraft will not be following a geodesic trajectory but instead (based on what I have seen of current mission planning) a pseudo-orbit circling, not the asteroid's center of mass, but a center sun-wards of the asteroid's location. This would lead to a geometrical dilution of precision between the precisely determined (Earth to spacecraft) radial range and range-rate to the ARRM spacecraft and the length of the non-radial directions to the asteroid. I urge that the ARM mission consider the use of phase-connected Very Long Baseline Interferometry (VLBI) of the ARRM spacecraft during the gravity tractor phase of the mission to improve the transverse accuracy of the spacecraft orbit determination. The Joint Institute for VLBI in Europe (JIVE) uses this technique routinely for spacecraft tracking; either JIVE or the Deep Space Network (DSN) or the VLBA (in the US) should be able to provide highly accurate determinations of the ARRM spacecraft's angular position using differential VLBI. Routine VLBI determinations of the spacecraft's position (to ~ 0.1 nanoradian, or about 15 meters in both transverse directions at a distance of 1 AU) should help to determine the gravity tractor effect, and also provide an independent check of the accuracy of the Doppler + LIDAR tracking system.*

- *I would also like to urge that the ARM mission consider the distribution of small laser retroreflectors on the surface of the target to serve as laser fiducial points. My company, as part of a consortium lead by the Royal Observatory of Belgium, proposed this to the European Space Agency for use on the AIDA / AIM kinetic impactor test mission (which also has a need to accurately* *determine the position of its target asteroid). Laser retroreflectors for use over a few km distance can be very small (~ 1 mm) and lightweight and provide fiducial points which have proven to be very important in terrestrial geodesy. These retroreflectors would ideally be distributed during the initial characterization period, and could be mounted on picosatellites sent to the asteroid surface (if that technology demonstration is accepted). If boulder capture or other surface operations result in significant surface motions, it should be possible to track the actual flows, and not just surface shape changes, through LIDAR to the fiducial points.*

III. ISRU

It is important to realize that there will be a strong commonality between the techniques needed for Asteroid Resource Extraction (or, Mining), and those needed for ISRU. In the beginning, Asteroid Mining will extract resources in situ from asteroids and deliver these resources to customers, and these customers could include, e.g., astronauts on their way to Mars orbit or living in a Phobos habitat. Many engineering and scientific developments needed for Asteroidal ISRU are part of the core ARRM mission already, and thus do not need particular attention here. One that does not seem to be is water; water is likely to be the first resource to be "mined" from asteroids. (My company, in particular, is interested in extracting water from asteroids and delivering it to astronauts in long-duration stays in deep space, either in habitats such as the planned Phobos habitat, or even in transit to and from Mars.) Attention should be paid to the availability of water in and around the target asteroids, which also would be of some scientific interest:

- *The ARRM should attempt to characterize the amount of water being released from the target asteroid, either by direct observation (e.g., by a time of flight mass spectrometer) or afterwards (say by the exposure of water traps at the asteroid's surface.*

- *The ARRM should attempt to immediately collect a sample from directly underneath the collected boulder, where regolith may have been hidden from the Sun for a considerable time, and thus might serve as a trap for water and other volatiles outgassed from the interior of the body. (In addition, if the boulder itself was found to contain volatiles, a sample from underneath would help to constrain whether these were intrinsic to the boulder, or were somehow derived from the asteroid's interior.)*

- *The acquisition of the boulder itself would be very useful in developing the technologies that will be used in future asteroid mining, as the capture of a boulder will surely be one of the major ways that materials are removed from the surface of asteroids.*

- *The acquisition of a core sample would also be of great interest to Asteroid Water Mining, and for mining in general. In much the same fashion that it is technically easier and generally cheaper to pump out underground petroleum rather than to dig it out, Asteroid Water Mining would ideally use piping and pumps as opposed to overburden removal to extract water, whether locked in phyllosilicates, or frozen in the center of an asteroid. The acquisition of a core would provide information both about the feasibility of driving such piping into an asteroid and whether there is a distribution of water and other volatiles at shallow depths. (In addition, a mechanically driven core sample would help decide whether it would be possible to anchor equipment to an asteroid by simply driving spikes into its surface.)*

IV. CAPABILITY/TECHNOLOGY DEMONSTRATION

Of course, some aspects of technology demonstration have been previously discussed. (Indeed, from the standpoint of Asteroid Mining, the entire ARRM can be viewed as a technology demonstration of likely mining techniques.) However, there are other possible technology demonstrations that I think that the FAST should consider:

- *The ARRM should consider including a test version of the new JPL Deep Space Atomic Clock (DSAC). The DSAC would provide adequate frequency stability to allow for one-way Doppler and Range tracking which (with differential VLBI) would substantially reduce the need for DSN tracking time during the gravity tractor phase of the mission. These capabilities would be especially needed if the ARRM was subsequently sent to Phobos for sample acquisition. The DSAC will be an essential element of any future global satellite positioning system for Mars; the ARRM mission could help develop and demonstration this crucial future technology for Mars exploration.*

- *It seems clear that asteroid exploration and prospecting will make extensive use of small nano- and picospacecraft (roughly, 1 kg and 10 gm, respectively). My company has proposed the use of our "Pixie" model "FlatSat" picospacecraft for the ESA AIM mission. (A FlatSat is a picosatellite that will fit within the CubeSat form factor in two dimensions, i.e., is no more than 10 x 10 cm, and is no more than 5 mm in the third dimension.) Our Pixie FlatSats fit within a 80 x 35 x 5 mm profile, and are intended to deliver a sensor or sensors to the surface of an asteroid. In a multiple asteroid exploration or prospecting mission, where the main spacecraft will not be able to actually land on each body investigated, such picospacecraft will be an essential tool of asteroid exploration and prospecting. I think that the FAST should consider the deployment of these or other similar designs (such as the ChipSats developed at Cornell University) as engineering demonstrations which can also provide useful scientific information (for example, in the AIM proposal the Pixies would carry cameras, magnetometers and accelerometers to the surface of Didymos beta to observe conditions before and after the kinetic deflection test). The same or similar designs could be used on the ARRM target to monitor surface changes during the boulder extraction process, and demonstrate the utility of this new technology.*

- *I am involved with a JPL / CalTech effort to demonstrate bi-static radar reflections from Europa using the very strong decametric emissions from electrons flowing in the Io-flux tube. As you know, I also feel that this technique could be used to examine the interiors of asteroids with a single receive antenna (as opposed to more complicated techniques using pairs of cooperating spacecraft, as in the Rosetta / Philae implementation of CONSERT for comet 67P/Churyumov-Gerasimenko). I think that demonstration of this technique for an asteroid would be a valuable technology demonstration and could return useful information about the ARRM target.*

I certainly understand that the ARRM may not be able to implement all of the technology and procedures that I have described in this note, but I wanted both to bring my thoughts to your attention and to indicate the issues that I would bring to the attention of the FAST.

Input from William T. Taylor (no affiliation cited)

To the FAST leadership,

I have read the Asteroid Redirect Mission FAST draft for public comment, and wish to offer commentary and suggestions as constructive criticism. The report was very technical and ought to provide a great impression, especially in regards to asteroid 2008 EV5. More details about the ARM spacecraft itself would have been more encouraging, although it is understandable the mission is very tenuous at this stage. I'll elaborate further.

The largest concern I have is how ARM meshes into the Journey-To-Mars plan colorfully displayed in numerous NASA documents. The publicly known objective of ARM is to bring a significant asteroid sample into orbit around the Moon. While there are sound ways to rationalize this, stating that comes off as counter-intuitive or even hypocritical in the public eye; the President made it clear there wouldn't be a Moon mission and that the asteroids missions were stepping stones to Mars orbit. It comes off as backwards to "bring the stepping stone to the Moon", which is how the media will interpret ARM. A firmer connection to the endpoint destination, Mars itself, would be wise to reinforce in place of asteroid exploration.

The best compromise between the nominal ARM plan and a human Mars mission would be to send ARM to the Martian moons, Phobos and Deimos. This approach is sensible in part because both Phobos and Deimos are essentially asteroids, and the same approach to sample acquisition at 2008 EV5 would function the same at either moon in their micro-gravity. Secondly, the President's plan cited Mars orbit as the goal; by definition the Martian moons are in orbit about Mars, making a visit to them one-and-the-same as the initial Presidential order to NASA. Thirdly, a Deimos/Phobos-bound ARM traces the same path taken to Mars, especially for slower cargo vessels; emphasizing this point especially transforms ARM from a "backwards-curiosity" into a "prototype for the Mars missions"...which make a superior way to garner public support. Finally, a sample returned from the Martian moons would have greater value as it could verify if the moons are a resource to capitalize on for In-Situ-Resource-Utilization; to-date none of the orbiting probes have answered this question, but a sample obtained thanks to ARM would be a valuable contribution to human planning, especially if the moons turn out to be rich in water (yet another question other robotic probes can not confirm or deny).

The aspects of ARM that can be respected, as is, are how it spearheads useful technology. Solar-Electric-Propulsion is a great idea to push since it is the safest and most efficient way to reach, arrive, and depart from Mars. Likewise, advancing the laser communication LADEE tested in lunar orbit would be a boon to both human and robotic explorers at Mars. If it can be applied to a human spacecraft, it would be worth flying.

In summary, to preserve the intent of ARM to assist human exploration, I suggest the follow policy changes beginning with highest-priority:

1) Target Phobos/Deimos in place of NEOs to better connect with the ultimate goal of Mars orbit/Mars.

2) Emphasize how a Phobos/Deimos-ARM will follow the same route as crewed Martian expeditions.

3) Stress how a sample of the Martian moons can identify usable resources and test extracting them ahead of human flights.

4) Test technology useful to crewed vehicles and especially vital to cargo vehicles.

With the upcoming administration changes in the U.S. government, there will be some inevitable changes in turn to NASA. As it is, ARM receives more negative than positive criticism. It has a better chance to survive such changes if it aligns more closely to the Martian destination. At the risk of being blunt, it would be too easy to imagine Donald Trump storming in and dropping his signature "You're fired," but that is an example of what NASA may face in the near future. A better example would be an SEP-guided craft flying out of the Lunar proving ground toward Mars.

I do wish the best for the research going into ARM; in many ways it has great potential for the BEO paths of human spaceflight.

Best regards,

William T Taylor

Input from Edward L. Patrick (Southwest Research Institute)

To whom it may concern:

I was appalled to find that the word "gauge" appears nowhere in your entire document. Furthermore, the term "pressure" only appears in the context of solar radiation and aerodynamic effects. The phrase "mass spectrometer" only appears once.

And this mission is supposed to return some science?

The last pressure gauge applied to a regolith-laden surface was the Cold Cathode Gauge (CCG) placed in 1971 during Apollo 14. The last instrument placed at a regolith surface to conduct mass spectrometry was the Lunar Atmospheric Composition Experiment (LACE) placed during Apollo 17 forty-three years ago next month (December).

If there is any belief whatsoever that the asteroid 2008 EV5 is hydrated, then it is a science imperative to monitor the local exosphere about that asteroid and volatiles that will most certainly evolve from it upon encounter with the spacecraft and its necessary tools.

The best analytical tool for probing such a body would be a time-of-flight mass spectrometer (TOF-MS). Hunter Waite at Southwest Research Institute has a prototype multi-bounce time-of-flight (MBTOF) mass spectrometer. If costs and TRL are a concern, then a quadrupole mass spectrometer (QMS) could be included in the payload at relatively low cost. Paul Mahaffy's group at Goddard Space Flight Center has spare QMS parts sitting around in drawers. Danny Glavin knows this.

The least expensive QMS on the market is that sold by Extorr in Pennsylvania. Thirty of their units were purchased by ISRO to make flight-worthy for India to fly to the Moon aboard the Moon Impact Probe (MIP) of Chandrayaan-1 that crashed into the lunar surface.

The Extorr can not only be made spaceflight-worthy, but it sports an onboard Pirani gauge and ion gauge integral to its ionization source optics. This mass spec sells for as low as $3450 in its terrestrial form. Surely NASA and the space science community can afford to include adequate pressure monitoring and analytical chemistry diagnostics for the encounter, probing and removal of the first boulder from another solar system body.

The loss of science from failing to monitor such gas and volatile evolution from an asteroid will keep the models and scientists as blind and ignorant as we have been with over 40 years of undefended assumptions made about the exosphere of the Moon. Now that we know LADEE could find neither hide nor hair of Chang'e-3 or its Yutu rover, there is at least some question in this scientist's mind as to what mechanisms are at work within regolith surfaces that enable the capture and retention of volatiles (and these would include Hg, K & Na). The understanding of these conditions for surface-bounded exospheres (SBEs) has implications for Mercury Europa as well, and not just for planetary protection, but for "science protection" as well.

Please don't tell me we're going to an asteroid without so much as a frickin' ion gauge. Just saying.

Best Regards,

Ed

Input from Walter Barry (Aerospace Systems and Training)

Dear HQ-ARM-FAST,

I read your ARM document and below I have a basic design of a lunar orbit space ship that could bring the bolder back from lunar orbit. The arms can be configured with the magnetic netting for asteroid materials conductive to magnetism or without for nonconductive materials. The ship can be configured without wings or with them providing a return to Earth. The ship below is configured without wings. The ship can also retrieve space debris such as old satellites and rocket junk.

Thank you,

Walter Barry

CEO Aerospace Systems and Training

Input from Edward Strobach (University of Maryland, Baltimore County)

Below are comments and questions related to the draft report from ARM FAST.

Question 1: Has there been an interest in using a gravimeter to probe subsurface structure and density variations? This might be useful for determining a potential candidate for a landing site.

Question 2: Through reading one of the sources, I found that the LIDAR footprint (didn't specify at what distance from the surface) was 7m X 12m area. This seems problematic when determining the vertical height (c) for boulders smaller than the LIDAR footprint. What LIDAR pulse length would be considered appropriate for probing height variations, and to what accuracy? Is there a certain LIDAR--with little beam divergence and high vertical resolution--that is both feasible and available for determine vertical variations?

Question 3: Are there alternatives for measuring the vertical dimension c of boulders besides through laboratory experiments and LIDAR? Could a high resolution camera be used to determine c? In other words, could we use the solar angle and the position of the surface relative to the sun, along with the length of the shadows caused by boulders along the surface to determine an approximate height?

Question 4: It wasn't clear, but is one of the intents to observe differences in upwelling radiation rates as 2008 EV5 rotates to determine variations in thermal inertia?

Edward Strobach
University of Maryland, Baltimore County

Research Assistant
PhD Candidate in Atmospheric Physics

Input from Michael Busch (SETI Institute)

I have a number of comments on the draft ARM FAST report, which are given below. I have split them into two sections: comments on the content of the draft report, and typographical suggestions.

I hope these are useful to you, and thank you for making the draft report available!

Michael W. Busch
SETI Institute

Comments on Draft Report Content

Page 4: It seems like a good idea to specify that the yellow shading in Figure 1 denotes those areas of EV5's surface that were either invisible to or only seen at grazing incidence by radar observations.

Page 5: The answer to question 1 here is a bit confusing to me. I had to reread it to understand which sentences refer to a high-temperature episode in EV5's past and which don't.

Page 5: Would it be a good idea to make EV5's origin in a disruptive collision explicit here?

Page 5: Why is the focus in the Executive Summary on 2-3 m blocks and not on 2-4 m blocks?

Page 8: In answer to question 4 here, why would a "narrow" distribution of strengths be expected? Or is "narrow" here to be understood only as relative to the wide range of properties across the whole NEA population?

Page 8: The last sentence in the answer to question 4 seems to assume that EV5 is not a CI or CM chondrite. But those are some of the most likely compositions for EV5, so that assumption would be misplaced.

Page 10: Radio science / gravity field mapping is not explicitly given in the list of investigations. Would it be better to separate it out from the rest of the current "global mapping of asteroid" investigation topic?

Page 11: Is it appropriate to mention a precursor mission here? Is there time for one, even with a joint launch with ARRM ? I note that other than a brief mention on page 65, what a potential precursor mission would do is not described anywhere in the draft report.

Page 17: Related to points both here and elsewhere in the draft report, I caution against uncritical *use of the effective diameter value of 370 ± 6 m from Alí-Lagoa et al. 2013 . The thermophysical modeling described in that paper failed to include significant sources of uncertainty - specifically the uncertainties the EV5 shape model as described in Busch et al. 2011, and the possibility of variations in thermal properties across EV5's surface. So the uncertainty Alí-Lagoa et al. assigned to their effective diameter estimate for EV5 is almost certainly far smaller than it should be.*

Page 17: Both here and on page 78-81: It is not clear to me what the spectral analysis by Cloutis is based on. i.e. which spectra, taken at which times by which telescopes at which wavelengths and using what range of possibilities for the overall albedo?

Page 18: Would it be a good idea to note the likelihood of past variations in EV5's spin axis here? This is relevant to the past temperature distribution across surface; and potential past heating of boulders.

Page 24: Radar observed far more than 1/2 of EV5's surface (e.g. see Figure 1). The limitation is that we can only identify candidate boulders over 1/2 of the surface.

Page 24: I would say "prominent concavity" rather than "putative crater" or "likely crater".

Page 25: The radar image resolution was 7.5 m/pixel in range. Do not trust the shape model at scales smaller than ~15 m.

Page 36: It is not a given that boulders on a given object would be homogeneous. This is discussed some on pages 37-38, but it seems misleading to focus on Murchison and Murray and to neglect meteorite falls with more heterogeneity such as Kaidun or Tagish Lake.

Page 39: As for page 8, this seems to assume that EV5 is not a CI or CM analog - which is not a given.

Page 42: The Figure 9 described in the text is not the Figure 9 included in the document. One or the other needs to be changed.

Page 52: As on page 10, radio science / gravity mapping is combined with imaging under "global mapping of asteroid". Better to separate it out to make it more explicit here as well as in the summary list; with applications for proximity operations and the GT demo as well as understanding EV5's interior ?

Page 55: Better to specify that "break the chain" means "break the chain of contact" and what that means?

Page 80 & 81: As for page 17: It is not clear to me where the spectra included here came from.

Page 86: The reference for the Chang'e 2 image of Toutatis in Figure 19 should be Huang et al. 2013, in Nature Scientific Reports 3 (paper #3411).

Page 93/94: As for Page 24: Nearly all of EV5's surface was observed with radar (excepting the north polar area). But we can only identify ~10 m scale boulder candidates over ~1/2 of the surface.

Page 96: As for Page 25: The radar image resolution was 7.5 m/pixel in range. The shape model resolution is 15 m or greater.

Page 104: The gamma correction for Figure 26 should be adjusted to better show the boulder candidates. It might also be a good idea to adjust the gamma corrections for Figure 19 and Figure 25.

Typographical Suggestions

Page 2: Typo in the title of Appendix B2 in the Table Of Contents.

Page 4: Word missing in the last sentence of the first paragraph on this page.

Page 4: Were there exactly 100 applicants to be on the ARM FAST? Or should that be "more than 100" ?

Page 13: Better to write "subsequent missions ... would also be facilitated ..." ?

Page 14: Better to write "and at optical and infrared wavelengths" ?

Page 16: There seems to be no reason to include a reference section or a reference to Busch et al. 2011 on this page.

Page 17: Better to write "allowed it to reach its current orbit" ?

Page 17: Reference should be to " Alí-Lagoa et al. 2013".

Page 18 and Page 70: Better to write "reached peak temperatures greater than" ?

Page 22: The wording in the first sentence of the reply to the power law distribution question is garbled.

Page 22: The second through fourth paragraphs on this page are duplicates of material on page 21. Likewise, Table 2 is a duplicate of Table 1. Is seems unnecessary to repeat everything.

Page 26/27: The last sentence on Page 26 is garbled.

Page 33: There is a problem with formatting for the reference attached to Figure 6.

Page 41: Formatting at the bottom of the page is garbled. Also, move Table 8 a bit further down in the document?

Page 49: Typo. "imageing" should be "imaging".

Page 85: Should read "Chang'e 2". Note lower case "e".

Pages 90 & 91: As for Pages 21 & 22, there is duplication of content between these two pages.

Input from Paul B. Huter (PBHspace)

To Whom It May Concern:

I have developed the basics for a solar-electric propulsion system that has the capability to transfer 13 metric tonnes from LEO to GEO, and I believe it would be a good candidate for transferring a 27 m^3 boulder for the ARRM.

Additional work needs to be carried out to refine the concept and make it viable for moving a 20 metric tonne boulder from the asteroid to Earth, but I wanted to make you aware of this concept.

I have an article published in the American Astronautical Society's September/October issue of "Space Times", and I can provide additional details on request.

Thank you.
--
Paul B. Huter
Spacecraft Engineering Consultant
PBHspace

Input from Antonella Barucci (LESIA-Paris Observatory)

Dear Dan,

I gave a quick look at the ARM_FAST report. It is an impressive piece of work. Just a comment on the spectra analogy.
The available data are very noisy and not of high quality, so it is very difficult to give a good analogy with meteorites, even if the more similar could be CI or CR meteorites.
Phase function effect needs also to be taken in consideration (albedo & spectra).
The mission is absolutely appealing and for sure, from what we know, 2008 EV5 is different in composition and complementary of Bennu and Ryugu.
We have some old data (spectra not at high quality), but we can check again and I will let you know if any new stuff.

Our lab is specialist on V-NR spectrometer, so let me know if there is any interest on international payload.

Best regards,

Antonella

Input from Patrick Michel (Observatoire de la Côte d'Azur)

Dear Dan and all,

I have read the ARM report, which was a great pleasure for me to read despite a dense agenda. So, I did as fast as I could and did not read all sections with the same level of attention (I focused on those matching my expertise). I attach to this email a list of comments/suggestions as well as a file with a compilation of material properties that I did some time ago (to be used for Table 7 in the report, if you want). Please use whatever you think is relevant and helpful. I'm more than happy and motivated to help as an international partner, if appropriate, or just as a colleague.
Good luck (merde, as we say in France!!) and best regards,

Patrick

Please see accompanying attachment.

Input from Laszlo Kestay (United States Geological Survey Astrogeology Science Center) -

Please find comments in the attached pdf.
Thank you,
Laz
--
Laszlo Kestay
Director
Astrogeology Science Center
United States Geological Survey

Please see accompanying attachment.

Input from Raffi Sahul (TRS Technologies)

Dear NASA FAST Team,

Please find attached our comments on the FAST Report and also a white paper illustrating the potential for development efforts for an Ultrasonic transducer that may help with the FAST program.

Thanks,

Raffi

Raffi Sahul, Ph.D
Director of Business & Product. Dev
TRS Technologies Inc

Please see accompanying attachment.

Input from Mark Sykes (Planetary Science Institute)

Inputs into the the mechanical design and mission requirements for ARM are necessarily highly speculative. Input from OSIRIS-REx and Hayabusa 2 cannot be used (which is recognized, but space is still taken up with it). In-situ observations by ARM are of no value to design and requirements, but necessary, of course, for deciding what is the best thing to grab assuming there is something grabbable.

The relevance of ARM to the human exploration of Mars is not at all well-supported. Simply pointing out some minimal relevance is insufficient. There has yet to be a complete flow down of Mars requirements from which an argument can then be made that a group of those requirements can be most cost-effectively addressed to the level needed for a Mars mission by executing ARM.

A reference model of the target asteroid needs to be defined at a sufficient level of detail to be usable to define design requirements for ARM, with clear parameter uncertainties. Then it would be possible to decide what range of uncertainties of what parameters (that may well be correlated) can be accommodated at what cost. It would also be possible (and needed) to then do a full-up risk assessment. There is a lot of good information in the report about various asteroid size, shape, mechanical, etc. property ranges. But no recommendation of a reference model is made (perhaps I missed it somewhere?), and there is little discussion of the potential impact on mechanical design of the parameter ranges.

Mark V. Sykes, Ph.D., J.D.,
CEO and Director
Planetary Science Institute

Input from Richard P. Binzel (Massachusetts Institute of Technology)

Public comments for inclusion in Final Report of:

Asteroid Redirect Mission (ARM)
Formulation Assessment and Support Team (FAST)

These comments pertain to the "Draft for Public Comment" (Dated November 23, 2015).

Author of these comments:
Richard P. Binzel
Professor of Planetary Science
Joint Professor of Aerospace Engineering
Massachusetts Institute of Technology
Cambridge, MA

Four specific criticisms are submitted:

1) The purpose of this document is to support a Technical Interchange Meeting. Yet this document contains statements that ARCM provides "a compelling focus" (p. 3) and a "compelling science focus" (p. 15) for the early flights of the Orion program.

a) This report does not have the authority to make any statement or implied finding regarding whether the ARCM concept is "compelling," as the study group members provided only non-consensus, non-voting input.

b) Two advisory groups to NASA with the authority to produce findings have reached the opposite conclusion. Their findings are quoted here so that this report in its final published form fully and fairly presents the balance of informed expert opinion.
** NASA Small Bodies Assessment Group Finding July 2014: "The portion of the ARM concept that involves a robotic mission to capture and redirect an asteroid sample to cis-lunar space is not designed as an asteroid science mission and its benefits for advancing the knowledge of asteroids and furthering planetary defense strategies are limited and not compelling."*
** NASA Advisory Council Finding April 2015: "Maneuvering a large test mass is not necessary to provide a valid in-space test of a new SEP stage. We therefore find that a SEP mission will contribute more directly to the goal of sending humans to Mars if the mission is focused entirely on development and validation of the SEP stage. We also find that other possible motivations for acquiring and maneuvering a boulder (e.g. asteroid science, planetary defense) do not have value commensurate with their probable cost."*

2) Page 4 specifically notes that the target selection is not fixed to be 2008 EV5, nor is it fixed to be a C-type asteroid (page 4). Therefore any and all statements or assessments regarding a "science" or knowledge gain should stipulate whether that purported gain is target dependent. In other words, *this report should be specific for how any gain might be diminished (or increased) if sampling (for example) ordinary chondrite asteroid material.*

3) Five “unique” knowledge gains are purported for ARM (p. 11 and p. 65), yet 4 out of 5 are not unique to ARM and can be accomplished with existing meteorite samples on Earth or through existing missions.
a. Subsurface sampling (core sampling) unaltered by the space environment is not unique to ARM as this is possible today on Earth for an abundance of meteorite samples having dimensions ranging from tens of cm to meter scale.
b. The requirement for multiple kg of samples is not uniquely satisfied by ARM, where instead for example, the Smithsonian Institution houses approximately 5 TONS of meteorite material. Experiments that might result in the destruction of large masses of samples are far more likely to be approved for the abundance of meteorite material compared to the very expensive (cost per kg) ARM samples returned to an Earth laboratory.
c. ARM in cis-lunar space is not uniquely required for an “orbital laboratory” to demonstrate asteroidal ISRU methods. These methods can be evaluated in Earth-orbit where 10s to 100s of kg of meteorite (or simulant) material can be delivered to LEO for lower cost and even lower astronaut risk as compared to ARM.
d. ARM is not in correlating asteroid spectral properties to surface samples as this has been accomplished previously by the Japanese Hayabusa mission and will be accomplished by Hayabusa II and NASA’s own OSIRIS-REx mission.

4) Throughout this document [most specifically Tables 9 and 10], assessments are made about “science” gains with no traceability to specific NASA Science Objectives or to Planetary Science Priorities described by the Decadal Survey. Declining traceability (p. 11, p. 65) precludes any and all substantiation of merit to any statement or tabulation pertaining to “science” gains.

One recommendation / suggestion is offered:

5) Rather than grasping for “science” that is unsubstantiated by any traceability or discernible merit, this report should much more strongly and much more directly delineate its traceability and essential knowledge gains as they pertain to Phobos. (For example, Tables 9 and 10; and text throughout, indicate how and why each experiment delivers required information for a Phobos mission.) By including in this report much more direct assessment of applicability / relevance / importance to Phobos, ARM and ARCM gain specific rationale for how their investigation activities serve the Horizon Goal of Mars.

Input from Brent Archinal (United States Geological Survey Astrogeology Science Center)

Dear Dan and ARM FAST leadership:

I’m responding here with comments on the draft ARM FAST Report. Please see the PDF attachment to this e-mail. As noted there the FAST team has certainly done some impressive work in a brief *period of time. My comments are mostly in regard to some items that are not quite clear relative to asteroid and boulder mapping and characterization issues.*

Please let me know if you have any questions about this comments. Best wishes on your continued work on the ARM and with the Technical Interchange Meeting.

Regards,
- Brent

Brent Archinal
USGS Astrogeology Science Center

Please see accompanying attachment.

Input from Ed Scott (University of Hawaii)

See attached file.

Best wishes, Ed Scott

Accompanying attachment follows:

Comment on Asteroid Redirect Mission (ARM) Draft report

Expected strength of meter-sized boulders on asteroid 2008 EV5 and other C type asteroids

The draft report attempts to constrain the strength of boulders on 2008 EV5 using primarily bolide data and physical measurements on meteorites. Missing from the report is any discussion of the cosmic-ray exposure ages and breccia properties of meteorites, which both suggest that boulders on 2008 EV5 are probably very weak.

Cosmic-ray exposure ages of stony meteorites are typically 1-100 Myr and date the time when sub-meter-sized meteoroids were exposed to space. CI and CM chondrites have uniquely short cosmic-ray exposure ages of ~10^5 to a few times 10^6 years: mean values based on ^{21}Ne abundances are 1.8±2.1 and 2.8±3.1 Myr for CI and CM chondrites, respectively (Herzog and Caffee, TOG 2nd edition, 2014). The reasons for these short exposure ages are not fully understood but it is very probable that the lack of longer exposure ages for CI and CM chondrites is due to their very low strength. CR chondrites have longer exposure ages of 1-25 Myr, with an average of ~8 Myr.

CI, CM, and CR chondrites share a second unique characteristic: they are all breccias that contain solar wind gases (Bischoff et al., 2006, MESS II). [For comparison, the proportions for H, L and LL chondrites are 15, 3, and 6%, respectively.] The very low abundance of solar wind and irradiated grains compared with lunar regolith breccia meteorites probably reflects dilution with unirradiated grains (Roth et al., 2011, MAPS). CM, CR, and CI chondrites are therefore mixtures of materials with diverse alteration histories not rocks that were compacted by metamorphism, alteration, or *hydrostatic pressure. They were compacted by repeated impacts that locally decreased the porosity and caused low-level shock and deformation of chondrules (Lindgren et al., 2015, GCA). CM chondrites are nearly all shock stage S1 as more strongly shocked materials did not survive as coherent rocks. Similar processes probably affected the CI parent bodies as CI chondrites are all complex breccias containing solar wind gases (Morlok et al., 2006, GCA).*

Conclusions:
CI and CM chondrites, which are probably derived from boulders on their parent asteroids, have breccia properties and cosmic-ray exposure ages that the Strong boulders that are required for the Asteroid Retrieval Mission are likely rare or non-existent on CI and CM asteroids.
The parent asteroids of CR chondrites probably have somewhat stronger boulders than the CI and CM asteroids as shock levels in CR chondrites are mostly S2 and they have longer exposure ages.

Ed Scott
University of Hawaii
December 4, 2015.
