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Integrating Public Deliberation into Engineering Systems: Participatory Technology Assessment of NASA's Asteroid Redirect Mission[1]

David Tomblin[2]
University of Maryland

and

Zachary Pirtle,[3] Mahmud Farooque,[4] David Sittenfeld,[5] Erin Mahoney,[6] Rick Worthington,[7] Gretchen Gano,[8] Michele Gates,[9] Ira Bennett,[10] Jason Kessler,[11] Amy Kaminski,[12] Jason Lloyd,[13] David Guston[14]

We discuss an experiment employing participatory technology assessment, a public deliberation method for eliciting lay citizen input prior to making decisions about science and technology, to inform upstream engineering decisions concerning technical aspects of NASA's Asteroid Initiative. In partnership with NASA, the Expert and Citizen Assessment of Science and Technology network conducted a pTA-based forum on NASA's Asteroid Initiative in late 2014. The goal of the exercise was to assess citizens' values and preferences about potential asteroid detection, asteroid mitigation, and exploration-based technologies associated with NASA's Initiative. This paper discusses the portion of the forum that focused on the Asteroid Redirect Mission, an effort to redirect an asteroid into lunar orbit that astronauts can study. The forum sought public input on two options for performing the mission that NASA included in technical assessments to make a down select decision: Option A (capturing a 10 meter diameter asteroid) or Option B (redirecting a several meter diameter boulder from the surface of a larger asteroid). We describe the values and perceptions participants had about Option A and B, how these results were used by NASA managers, and the impact the results of the participatory technology assessment had on the down select.

Over the past two decades, a normative goal that many scholars of public engagement with science and technology invoke is a two-way dialogue between the broader public and science and engineering practices. One proposed way of achieving this is to incorporate participatory technology assessment (pTA) into the decision-making processes of institutions that have the power to influence the direction of scientific research and technological innovation[15]. However, one of the major critiques of deliberative exercises like pTA is that they rarely have impactful connections to decision-making processes[16], especially in the United States[17]. In order to fill this void, Stilgoe and colleague's model of responsible innovation necessitates going "beyond previous deliberative experiments so that governance institutions and structures become part of the experimental apparatus" (p. 1577)[18]. We describe herein such an experiment.

This article features an experimental public deliberation designed to inform upstream engineering of an asteroid redirection system being developed for NASA's Asteroid Initiative. To carry out the experiment, NASA partnered with Expert and Citizen Assessment of Science and Technology (ECAST), a network of universities, science museums, and non-profits invested in bringing the voice of the lay public into technical decision-making processes.[19] This effort afforded ECAST with a unique opportunity to experiment using pTA to develop linkages between deliberative public input and a concrete decision concerning a technical choice between two alternative asteroid redirection methods. What became known as the "Informing NASA's Asteroid Initiative: A Citizen's Forum" took place in November 2014 and represents a major step toward synching up pTA-style inputs into a U.S. government agency decision making apparatus.

While one of the goals of the NASA project was to provide lay citizens an opportunity to influence technical decision-making, this pTA experiment has also positioned us to contribute to the recent turn in public engagement scholarship that attempts to broaden the analysis of deliberative exercises to the institutional contexts in which they are implemented. Much research and commentary to date on pTA has focused on the potential for pTA to empower citizens and produce democratically legitimate outcomes[20]. This experiment provides the opportunity to better understand the institutional barriers and facilitators that contribute to pTA having a meaningful impact on the governance of emerging science and technology[21]. Our analysis represents a reflexive exercise where we explore the use of pTA to inform NASA's Asteroid Initiative and the lessons learned by the organizers (ECAST) and NASA personnel working closely together to implement the project. The authors of this paper, both members of ECAST and NASA employees, all played a role in developing and implementing "Informing NASA's Asteroid Initiative."

As a contribution to Chilver's observation that there is a dearth of "reflexive [institutional] learning relating to public dialogue on science-related issues,"[22] we aim to draw on our practical experience with the pTA design, implementation, and results dissemination to achieve four goals. First, we explicate a model that demonstrates how pTA is an iterative, co-learning input that can inform policy and technical decisions. Second, we describe the collaboration between NASA and ECAST to design the pTA. Third, we examine some of the results of "Informing NASA's Asteroid Initiative" and show what lay citizens can contribute to a highly complex technical choice between alternative technologies. Lastly, we describe how NASA engineers and managers used citizen input, which resulted in a generative dialogue between NASA personnel and ECAST during the development of the final report. We demonstrate how the results not only were used to support a decision, but also served as a reflection point for engineers and decision makers on their own values. Also, we provide a reflexive analysis of this experiment and consider how future engagements with federal agencies can be improved.

Participatory Technology Assessment and Engineering Systems Decision Making

While NASA is an agency that serves the public, the direct impacts of its missions are not always readily obvious from a casual examination. Much of its research is geared toward exploration and fundamental contributions to scientific knowledge. Since the end of the Cold War and especially after the end of the Space Shuttle program, NASA has continued to evolve its mission and how it describes its value.[23] Nevertheless, NASA engages in many domains of research that have direct benefits to society, such as monitoring the Earth's atmosphere for weather and climate change patterns and advancing capabilities for aircraft. Furthermore, NASA as an institution has some level of self-awareness of its need to justify its missions to the broader public. For instance, in a period of uncertain public support in the 1970s, NASA took a democratic tack with the Space Shuttle program as part of how it engaged the public.[24] This was an attempt at a more participatory exploration approach, where limited numbers of the public had an opportunity to be involved directly with NASA missions, mainly through sponsored research projects during shuttle missions. While this experiment was short-lived due to the Challenger disaster in 1986, NASA would later experiment more extensively with participatory democracy in the 21st century, through citizen science initiatives such as the Grand Challenges, maker fairs, and more recently with deliberative exercises like the pTA.[25]

These latter efforts are in response to NASA managers and engineers trying to develop systems and perform missions that will have significant value for the public. However, it is difficult to understand, especially through opinion polls, what members of broader society value on a deeper level, and it is even more difficult to consider public values prior to developing a mission. This is the context in which the pTA reported in this article came into existence. In 2013, NASA initiated citizen deliberations focused on what it called its Asteroid Initiative, which was defined as having two central components. The first is the Asteroid Grand Challenge (AGC), a planetary defense effort that seeks to detect all asteroid threats to human populations and determine appropriate mitigation actions. The second component, and the aspect most relevant to future human space exploration, is the Asteroid Redirect Mission (ARM). ARM will redirect an asteroid sample into vicinity of the moon, at which point astronauts will rendezvous with the asteroid to study it. At this early stage, NASA was debating between two mission concepts for ARM, one which would use an unmanned spacecraft to either redirect an entire asteroid or a second option which would redirect a small boulder from a larger asteroid and put it into a stable orbit around the moon.[26]

Decisions concerning which technologies to develop for ARM are highly technical and are not typical fodder for public debate. However, NASA managers and engineers became interested in learning what the public might value about different asteroid redirection options. This interest became a unique opportunity to experiment with linking pTA to engineers and managers involved in a technical decision-making process. Historically, many scholars have demonstrated that there is a tendency for technical experts, policy makers and stakeholders to avoid exposing the public to the complexity and uncertainty of scientific research and technological development because of prevailing perceptions that doing so slows down development of emerging science and technology (S&T).[27] However, this approach makes policy making and S&T development less transparent, thus more vulnerable to public distrust and ideological stakeholder entrenchment.

As an antidote to this problem, many advocates of pTA suggest that the complexity of emerging S&T issues should be opened up to discussion, emphasizing that increased transparency and a pluralistic dialogue can alleviate political pressures that often emerge in “winner takes all” policy debates.[28] This approach, it is proposed, can lead to the generation of alternative ways of thinking about complex technological systems and the social uncertainties associated with them, especially if engagement is conducted upstream to identify multiple potential pathways for technological development and their associated benefits and unintended physical and non-physical harms.[29] In this article we aim to show the ways lay citizens, through a pTA exercise, can open up discussions and expand the horizon of considerations for technical decision makers when developing new technical systems.

The pTA is a public deliberation method for assessing the societal benefit of research and empowering the public to consider decisions that some might otherwise think a lay public would be incapable of doing.[30] Citizen empowerment occurs in four basic ways: (1) generating policy input in the form of value maps (e.g., what values drive what people think about NASA missions and potential decisions); (2) building individual capacity to make informed decisions about complex technical subjects; (3) creating a sense of public ownership of decision making processes; and (4) developing a source of unique external technical input through a form of crowdsourcing. In short, it provides an informed and empowering environment for previously unengaged citizens to take ownership of complex technical subjects, build capacity to engage in complex subjects, and offer new views and consider the potential benefits, trade-offs, and long-term consequences of proposed policies or research directions.[31]

The path toward the “Informing NASA’s Asteroid Initiative” pTA began with a public Request for Information that NASA issued in 2013 to gather industry, academic and community interest in the Asteroid Initiative. The request for information sought ideas in eight domains related to the initiative, including one on partnerships and participatory engagement. ECAST’s response discussed how pTA could inform NASA about public perceptions of its Asteroid Initiative and what citizens value about space exploration. This response resonated with the agency as a promising means to gauge public views of this Initiative. In April 2014, NASA awarded ECAST a cooperative agreement to conduct public deliberations and identify citizen perspectives about the Asteroid Initiative.

ECAST’s implementation of pTA incorporates a transdisciplinary research design model,[32] and acts as a complement to techno-scientific discourse and sociopolitical discourse. The objective is to create an additional non-partisan public input to better inform scientific research, technological development and public policy. Therefore, it is a model that outlines the potential of linking public engagement with engineering systems design and decision-making processes. As illustrated in Figure 1, it has three steps: (1) Problem Framing; 2) Peer to Peer Discourse; and (3) Application and Reintegration. The problem framing and reintegration steps are co-developed/co-produced by ECAST and the decision-makers involved in systems design, keeping the peer-to-peer discourse (step 2) informed but sufficiently shielded from unbalanced and undue influence of technical and policy advocacy. In other words, the process is designed to highlight input from citizens that do not already have a vested interest in the decision in question. As a result, the theoretical outcome of the deliberation provides public views and insights that could be different from stakeholders with vested interests.[33] This is a different kind of input that technical decision makers at government agencies do not generally have access to or seek out.[34]

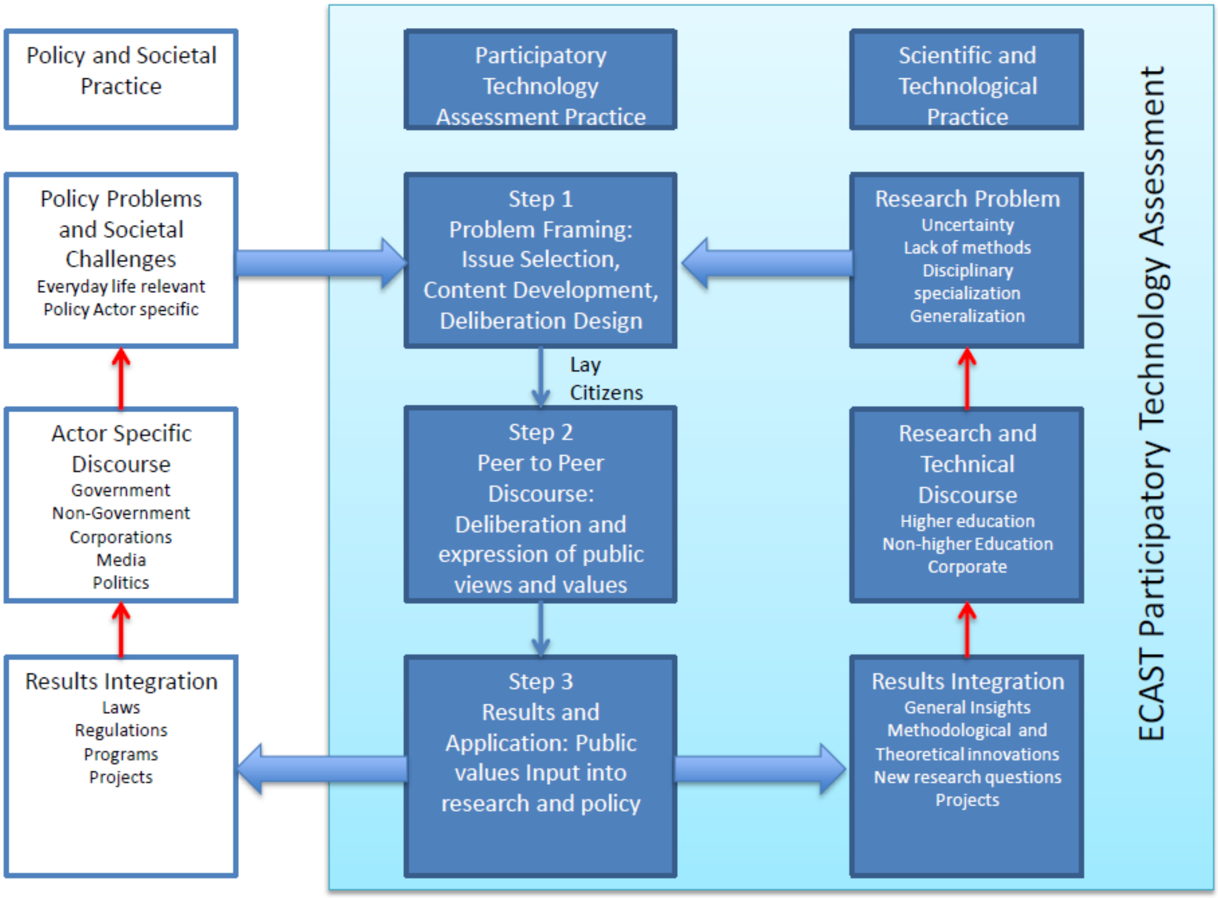

Figure 1. Transdisciplinary Research Design Model.

Notes: Early stages of policy development (left column) and research design (right column) feed into ECAST pTA process (middle column), which produces upstream public values, knowledge, and concern outcomes that can be incorporated into a feedback loop into policy and research development. Adapted.[35]

The first step in the "Informing NASA Asteroid Initiative" project was to plan and design public forums that engage citizens and solicit their informed views on issues of importance to NASA, which NASA could then use in its policy and engineering decision-making processes. The ECAST organizers and NASA program managers worked closely together to develop appropriate themes and content for the forums—a challenging task, since this project represented the first deliberative public engagement on this scale undertaken in partnership with NASA (Step 1, Figure 1). The planning process of partner consultation, content development, facilitator training, and participant recruitment took place from April to October of 2014; the one-day, in-person forums were held in November 2014.

ECAST designed the forums to explore what a diverse group of lay citizens thought about complex socio-technical issues when provided with information developed by a panel of experts on the subject matter (Step 2, Figure 1). Quite different from what a public opinion survey can produce,[36] the NASA pTA explored the value of different cultural perspectives, rationales, conceptualizations, and perceptions of risk that citizens use in assessing socio-technical issues as an experimental input into an engineering decision-making process. NASA expressed interest in learning about the perspectives and experiences that everyday people bring to considerations of the space agency's decisions. Thus, in addition to capturing quantitative data that could be aggregated and statistically analyzed, which is a typical strategy for NASA public affairs consultants, this project sought qualitative data to identify the various priorities and social norms underlying citizens' technical and policy preferences. ECAST then reported this data to NASA managers for further reflection. Consultations between ECAST and NASA proceeded through several iterations as NASA managers sought to understand and internalize the value of the results for their decision making (Step 3, Figure 1).

Deliberation Design of "Informing NASA's Asteroid Initiative" Project

ECAST came to the partnership with experience in social science techniques for structuring dialogue among citizens, including exercises that help participants debate specific, pre-selected issues,[37] ECAST organized two forums in Phoenix, Arizona and Boston, Massachusetts in November 2014, also leading the recruitment process and ensuring that demographics were roughly comparable to local populations. One hundred eighty-three citizens (97 in Phoenix and 86 in Boston) attended the two forums. At the request of NASA, ECAST worked to minimize self-selection biases on the part of space advocates among the participant pool. Drawing upon NASA's input, ECAST also developed informational content for citizens. Those attending the one-day forum were provided with read-ahead materials and spent the day learning about NASA's asteroid initiative. Structured discussions were enabled by a facilitator, with NASA personnel present in primarily an observational role. NASA personnel remained anonymous except for a single opening comment at each forum that expressed NASA's interest in knowing participant thoughts about the Asteroid Initiative and their plan to use the information in the Asteroid Redirect Mission down-select decision (meaning choice in NASA parlance). Several NASA personnel served on an anonymous question and answer (Q&A) panel that answered participant-generated clarifying questions on highly technical matters (e.g., the significance of asteroid de-spinning to different types of proposed asteroid redirection technologies) through an on-line interface where the questions and responses could be viewed by all participants.

In consultation with NASA, ECAST developed topics of discussion for participants. The overall forum covered four thematic areas that also included an informational planetarium show, several breaks, lunch, and the administration of a post-deliberation survey. The overall guiding questions for each theme were as follows:

1. *Asteroid detection*. Are citizens satisfied with existing asteroid detection approaches? What entity do they see as being best capable of leading detection efforts? This tied to the Asteroid Grand Challenge, which aims to identify all asteroid threats and to know how to mitigate them.
2. *Planetary defense*. After explaining four asteroid mitigation approaches, ECAST put forward a series of scenarios where asteroids have various percentage likelihoods of hitting the Earth. What levels of risk do people find unacceptable? How prepared do they want planetary defense capabilities in case of an imminent threat?

3. *Asteroid Redirect Mission (ARM) down-select*. In 2014, NASA spent significant effort internally deliberating over two competing mission proposals for ARM. Option A included grabbing a 10 meter (m) diameter asteroid and redirecting it to lunar orbit, and Option B involved grabbing a 3 m boulder off of a much larger asteroid.
4. *Mars exploration*. The ARM mission is part of broader plans to eventually explore Mars. What sorts of timeframes do citizens want exploration to occur in, and to what extent are they willing to trade schedule and cost for risk? To what extent do they want a full plan to go to Mars laid out now?

In this article, we focus on the results of the Asteroid Redirect Mission (ARM) session and its impact on technical decision-making at NASA.[38] The next section provides a brief history of ARM and an overview of the background information participants received to prepare for deliberation on this topic.

Context on Asteroid Redirect Mission

As ECAST began work on developing the citizen forum in summer 2014, NASA announced that it would down-select between two technological options, known as Option A and Option B, in late 2014 or early 2015 to accomplish the Asteroid Redirect Mission (ARM). At NASA's request, ECAST decided to focus part of the citizen forum on the ARM down-select, which was a decision between these two options.

The Asteroid Redirect Mission (ARM) was announced in April 2013 as part of President Obama's Asteroid Initiative, which was a way to implement his 2010 goal for astronauts to visit an asteroid by 2025. The several year mission as originally proposed, which would eventually become known as Option A, involved sending a vehicle, the Asteroid Robotic Redirection Vehicle (ARRV), to dock with a small (10 m diameter) asteroid, to envelop the asteroid in a bag, and then use a constant propulsive force to control the trajectory of the asteroid and slowly put it in the Moon's orbit. The asteroid would be inserted into a distant retrograde orbit (DRO) where it is estimated it would remain about a hundred years. Once there, the crewed portion of ARM would occur. Astronauts on an Orion spacecraft would be launched from a Space Launch System rocket and would rendezvous with the ARRV and the captured asteroid. Once docked, the astronauts would unfold the bag, collect samples and conduct other research on the asteroid.[39]

NASA's plans for this mission continued to evolve after it was first announced.[40] NASA scientists and engineers knew from the beginning that identifying target asteroids that would match the right orbital trajectory required for redirection might be difficult. Complicating matters, it could be hard to accurately predict the material characteristics of the asteroid prior to the ARRV arriving at the asteroid. The characteristics of the asteroid can influence what scientific questions may be studied with the sample, which meant that uncertain composition could make prediction of scientific value difficult. This led NASA to focus on a second option for accomplishing the robotic segment of ARM.

The desire for greater certainty on the structure of the target asteroid, as well as desire for more candidate options, led to Option B being developed.[41] This option involved traveling to a larger asteroid, greater than 100 m in diameter, where the probe would descend and land just above a boulder. The probe would use a set of robotic arms to grab the boulder, secure it, and remove the boulder using propulsion. The probe would then move the boulder to DRO around the Moon, where astronauts could dock with it.

The aim of the ARM mission down-select was to choose between Options A (inflatable bag) and B (robotic grabber). The following summarizes the background information given to participants at the forum. At a top level, both options would develop solar electric propulsion (SEP), which was the primary goal for the mission. SEP is a critical tool needed for human spaceflight missions, as it would make possible sending large volumes of payload to Mars with significantly less propellant, thus lowering the number of costly launches needed for exploration. Options A and B were equally beneficial in this respect. Option A would ostensibly retrieve the larger sample, but because of the technique's inability to accurately gauge the physical composition of the asteroid prior to capture, the mission potentially could retrieve a sample less than half the size of the targeted 10 m diameter, leaving its scientific value uncertain. In comparison, Option B would involve challenges with removing the boulder from the surface of the asteroid.

Despite these trade-offs, both would provide benefits for helping with planetary defense, but in ways specifically related to each method's technological capabilities. Option A could utilize an ion beam deflector and a so-called gravity tractor maneuver.[42] Option B could use the additional mass of the boulder to do what is known as an enhanced gravity tractor, where its influence would be significantly enhanced by the mass of the boulder. In the background information, Option B was described as more beneficial for planetary defense for that reason. Option B was also envisioned as having a use for developing a mission to Mars, as it could be used to retrieve samples from the moons of Mars, Phobos and Deimos. Option A has been discussed as having potential dual-uses for orbital debris removal from Earth orbit. Initial NASA estimates showed that the cost of both options would essentially be the same, with both costing less than $1.25 billion, meaning that cost was not a deciding factor between the two options.

The uncertainties involved with the two options varied in nature. Some uncertainties, as discussed above, are technical in nature. But other uncertainties, such as how to value the larger size of the Option A asteroid, the potential use to Mars missions, the potential dual-use for space debris removal, and the potential benefits for planetary defense, are all influenced by social values. As such, the ARM down-select had uncertain dimensions that could be affected by what values and preferences the public and decision makers hold. This background information about the trade-offs of each option, both technical and social, were presented to the pTA participants to consider. As the pTA effort developed, NASA continued its progress on the ARM. In December 2014, right before NASA planned its down-select, ECAST gave NASA an interim report on the ARM portion of the deliberation, which was reviewed as background information for NASA's consideration prior to its decision about ARM Option A and Option B.[43]

Deliberation Procedure

This session solicited both group and individual preferences for ARM Options A or B. The ARM session ran for 60 minutes, which began with a video that reiterated the background information given to participants prior to the forum. After the video, participants were given fifteen minutes to deliberate and share their reactions to the video. Facilitators at each table specifically asked participants to discuss the trade-offs between Options A and B, guiding the conversation to comparison points, such as potential scientific benefits and relevance to future exploration. After discussing the options, the participant had an additional 10 minutes to develop a written group recommendation for one of the two mission profiles and provide a rationale behind their choice. In addition to the group recommendation, facilitators asked participants to vote individually and provide personal rationales for their preference. Table 1 below provides a summary of participant derived benefits and considerations for the options.

Table 1. Summary of Benefits and Considerations on ARM options.

Option A	Option B
Mission Profile: Capture of an entire ~ 10 meter asteroid with inflatable bag system.	Mission Profile: Retrieval of a smaller (1-3 meter) boulder from the surface of a much larger (~ 100 meter) asteroid using a robotic "grabber."
Benefits • This technology could potentially be applied to the problem of clearing away space junk from low Earth orbit. • A larger asteroid would yield more samples and eventually be more valuable.	Benefits • The larger parent asteroid could be compositionally characterized before target selection, allowing a greater control over the properties of the retrieved object. • Operations on the surface of the larger object are likely to be relevant to future human exploration than capturing a smaller object.
Considerations • Is the risk that the target turns out to be a rubble pile rather than a monolithic object acceptable? • This option will require de-spinning the object before capture – an important capability to demonstrate for deep-space operations. Is this a compelling engineering challenge? • Does the smaller choice of targets make this option less interesting?	Considerations • This option will allow a gravity tractor demonstration on a much larger object than option A, which could help advance planetary defense against an asteroid threatening the Earth. Is this a compelling engineering challenge? • Is this option "cool" enough? • Will the ability to select from many different boulders lower risk and improve the mission?

The group and individual voting results from this session favored Option B (robotic "grabber"). At both sites combined, 21 deliberation groups out of 27 voted for Option B (4 voted for A and 2 voted for neither). The individual voting followed a similar pattern to the group voting, with participants choosing Option B (76 percent) over Option A (24 percent) by a significant margin.[44] While the voting results eventually aligned with NASA's decision in March 2015 to go with Option B, this is not the important result of the experiment. What ultimately was important was how NASA engineers and managers interacted with the participant rationales, conceptualizations, and expressed values for their choices. The next section explores what further can be gained by understanding how lay citizens introduce more socio-technical complexity into decision-making, provide diverse value maps; and develop rationales for their choices.

Results: Lay Citizen Contributions to Technical Decision-Making Processes

We used a multi-valent data collection approach, which relied on table observations, participants' written rationales, and quantitative votes. For table observations, we observed the full day of discussion at 8 of the 27 tables convened at the two sites. The individual rationales reveal nuanced information about participant values and opinions. In the discussion, we take a closer look at the qualitative table observations and written rationales to ascertain a deeper understanding of the participant values that drove the group and individual voting results. What is unique about this subset of the pTA deliberation is that it mainly focused on the trade-offs of a technical decision that has no inherent controversial elements associated with them.

Introducing Socio-technical Complexity to Technical Decision Making

Because of the technical nature of the decision, it made the deliberation of this topic an area ripe for participants to open-up new avenues of deliberation for techno-scientific decision-makers. While engineers and other techno-scientific decision-makers are generally leery of violating the technical/social value dichotomy, lay citizens are not as bound to such norms, thus can add to the socio-technical complexity of a decision.[45] To assess the degree to which participants used social versus technical language in their deliberations, we analysed 183 written participant statements concerning their rationale for choosing Option A or Option B. Statements that were dominated by explicit expression of social values were coded as primarily social (e.g., assertion of goals, derived benefits, potential, and societal concerns), whereas statements dominated by explicit technical language were coded primarily as technical (e.g., technical aspects such as gravity tractor, asteroid sample, data, and testing technology). We acknowledge that all techno-scientific statements have both technical and social elements. However, technical language embodies a higher level of abstraction that is more detached from specific, value-laden goals, obscuring the socio-political elements of technological development. By identifying the use of abstract technical language, one can discern individual tendencies toward separation of technical and social values, where people either consciously or subconsciously obscure social values through technical language.[46]

We found that roughly 70 percent of participant statements were dominated by social language, which, perhaps unsurprisingly, means that deliberations drifted more toward the social merits and concerns of the alternatives than the technical value and concerns. This also means that participants did not necessarily adopt the technical language of NASA engineers and managers to inform their choices. This is important to note because it represents on a general level how participants sought to increase the socio-technical complexity of the decision-making process, thereby increasing the diversity of values technical decision makers are exposed to.

Public Value Mapping

What sorts of reasons did participants use to justify their decisions? To garner a greater understanding of the diversity of ways participants viewed and conceptualized each option, we examined the same 183 statements responding to the prompt: "What were your primary reasons for your recommendation [of Option A or Option B]?" All words in each statement were examined to determine the primary rationales by which participants characterized their preference for Option A or B. Words were organized into categories based on similarity of meaning and use. For example, a common concept used by participants to describe why they chose one option over the other was "control." But the idea of control could be described in several different terms, including words like manipulate, maneuver, capture, grab, grasp, redirect, "lasso," retrieve, handle, and manage. Individual statements that contained at least one of these words used in the proper context counted as "control."[47] Also, a statement could be coded into more than one category if it contained more than one concept. For instance, the following statement, "Best helps with long-term goals of going to Mars and testing new technology," falls into 6 categories: help ("helps"), goal ("goal"), Mars ("Mars"), science ("testing"), exciting ("new"), and technology ("technology").-

Table 2 shows the distribution of concepts used by participants to justify their choices. Participants used a wide variety of concepts to justify their choices, which would typically be obscured by voting results or an opinion poll that NASA personnel use to gauge the public. Through this upstream analysis, NASA engineers and managers can think through the diverse ways that people come to understand and value emerging technology. While the leading rationale for choosing A versus B was scientific advancement (Science = 38.8 percent), one cannot consider this as a sole justification. Overall, no one justification dominates the participant dialogue. One has to consider a wide range of reasons because most justifications were multivalent. Many of the justifications expressed social values on an abstract level, such as the future potential (18.5 percent) of an option or its flexibility (12 percent) to play different roles. This suggests that for some that the asteroid redirection technology must have benefits that go beyond its primary mission. Other justifications hone in on a specific expression of values, such as planetary defense (12.6 percent) or going to Mars (16.4 percent). More specifically, certain concepts and rationales resonated with participants when picking Option A or B.

Table 2. Distribution of Concepts and Rationales Between Options A and B.

Rationale	**Option A**	**Option B**	**Combined (n=183 statements)**
Science	9	62	71 (38.8%)
Technology	7	32	41* (22.4%)
Sample	13	24	38* (20.8%)
Potential	6	28	34 (18.5%)
Success	8	25	33 (18.0%)
Control	7	24	31 (16.9%)
Mars	1	28	30* (16.4%)
Failure	4	3	7 (3.8%)
Gravity Tractor	0	29	29 (15.9%)
Exploration	1	24	28* (15.3%)
Planetary Defense	0	23	23 (12.6%)
Flexible	2	20	22 (12.0%)
Future	5	17	22 (12.0%)
Composition	7	13	22* (12.0%)
Landing	0	19	20* (10.9%)
Exciting	8	12	20 (10.9%)
Economic	7	11	18 (9.8%)

Proving Ground	2	12	17* (9.3%)
Data	1	14	15 (8.2%)
Help	0	12	13* (7.1%)
Space Junk	11	1	12 (6.6%)
Benefit	4	8	12 (6.6%)
Safety	3	8	11 (6.0%)
Mining	2	7	10* (5.5%)
Advance	1	8	9 (4.9%)
Practice	1	8	9 (4.9%)
Human	1	8	9 (4.9%)
Proven Technology	0	7	7 (3.8%)
Engineering	2	4	7* (3.8%)
Time	2	4	6 (3.3%)
Private	3	1	6* (3.3%)
Relevance	0	6	6 (3.3%)
Uncertain	0	4	5* (2.7%)
Ion	1	4	5 (2.7%)

Notes; All percentages are based on n=183 statements (Phoenix and Boston combined). Only coded concepts with 5 or more utterances are included in this table. When the Option A and Option B columns do not add up to the combined total in the last column, this means the remainder were rationales that did not support A or B.

Participants' reasons for choosing A or B varied considerably. Some of the more common reasons related to their interest in Option B were planetary defense (23 mentions) and gravity tractor technology (29 mentions), the latter of which is generally linked to improving planetary defense. Also, many people related the choice for Option B in terms of going to Mars, as Option B could be extended to Mars moon missions (28 mentions). People who chose Option A gave reasons related to collecting space junk (11 mentions) and collecting asteroid samples (13 mentions). In essence, individuals' reasons for choosing between Option A and Option B were varied and quite particular. People may have been biased by their own particular concerns. For instance, those who chose Option B also perceived this technology as being more in line with planetary defense, which was dealt with extensively earlier in the day; thus during the day, it might have become a more immediate concern. Others may have been looking at this through their desire to see economic gains come out of these ventures (e.g., mining), while others were driven by aspirations to explore (e.g., going to Mars), or concerns about the increasing amounts of space junk in Earth's orbit.

In summary, we did this analysis to point out the diverse ways that lay citizens can think about a highly technical decision. The main take away from this analysis is that it provides technical decision-makers much to think about in terms of aligning goals of NASA missions with public desires. For instance, NASA managers and engineers were "surprised" to see to what extent the participants desired that the priorities of ARM should align with planetary defense. Table 3 shows that planetary defense was just as important to participants as scientific advancement and exploration. Beyond being able to reflect on the diversity of values that people invoke when thinking about deep space exploration, decision-makers became very interested in how participant rationales are formed. This allowed them to understand that people possess the ability to think through complexity in a variety of ways.

Table 3. Average Priority Rankings of Potential Goals of the Asteroid Redirect Mission.

GOAL	MA	AZ	COMBINED	P<0.05
ADVANCING SCIENCE	2.76 (1.40)	2.51 (1.78)	2.63 (1.62)	A
ADVANCING PLANETARY DEFENSE	2.54 (1.81)	2.85 (1.63)	2.71 (1.72)	A
ADVANCING TECHNOLOGY NEEDED FOR HUMAN SPACEFLIGHT	2.65 (1.40)	2.87 (1.78)	2.77 (1.62)	A
REDIRECTING AN ASTEROID THAT NO ONE HAS BEEN TO BEFORE	4.01 (1.82)	4.71 (1.73)	4.38 (1.81)	B
DEVELOPING THE ECONOMIC POTENTIAL OF ASTEROIDS	4.67 (1.45)	4.36 (1.85)	4.51 (1.69)	B, C
ENGAGING WITH COMMERCIAL AND INTERNATIONAL PARTNERS	5.00 (1.54)	4.86 (1.56)	4.93 (1.55)	C
PERFORMING AN EXCITING MISSION	6.05 (1.26)	5.68 (1.71)	5.86 (1.52)	D

Notes: Numbers in table are on a scale of 1 – 7 (1 = highest priority; 7= lowest priority). The goals are arranged in ascending order from highest to lowest priority based on voting in Massachusetts (MA) and Arizona (AZ) combined. The voting in Massachusetts and Arizona are consistent. The letters in last column refer to the "Combined" category. Categories that do not share a letter are statistically significantly different at p<0.05.

Understanding Lay Citizen Rationales

Participant rationale formation is also an important dimension of a deliberation for engineers and managers to consider. The citizen conceptualizations and rationales outlined in Table 2 only offer preliminary insights on how people are thinking about the two options. Analysis of the table observation data and written rationales demonstrate that participants successfully navigated and effectively incorporated scientific and technical details into their discussions and considerations for ARM A or B.

One way to judge the utility of the deliberation in providing space for the development and expression of informed views by members of the public is to directly observe the conversations among participants.[48] If one observes at a table discussion over the course of a day that participants drift among topics or simply cannot understand important technical issues sufficiently for forming an opinion about them, the utility of the deliberation clearly is called into question. On the other hand, if the participants engage with the complexity of the issues and provide a clear rationale for their views, they have attained a level of informed and considered insight that can be useful to decision makers. To determine the efficacy of the table discussions, we used table observation data to shed light on two questions: what was the quality of the deliberation; and what reasoning did the participants use in developing and expressing their views on the questions put to them in the course of the day?

An analysis of the data from four table groups provides considerable evidence that the quality of the discussions was high in many fundamental regards. Furthermore, this analysis provides some insight into the common features of participant discussions and the variety of rationales adopted to support Option A or B. Of the four tables analyzed here, one group supported Option A (see Box 1 below), two groups supported Option B, and one group was split over A or B. This analysis revealed some challenges and unevenness in conversation, though the deliberations reflected strong and thoughtful communication among citizens.

At all of the tables reviewed here, all or most of the participants contributed their thoughts; most or all of the issues and arguments raised in the background materials and videos were considered by the participants; and participants often used the anonymous expert Q&A resource to clarify technical questions and misconceptions. While some participants spoke more than others, there were no instances in which one or two dominated the discussion (even at one table that included a master's and a Ph.D. student in astrophysics); there were few uncorrected errors or misconceptions in the discussions; when confusion about technical issues emerged (e.g., the importance of de-spinning an asteroid for A and B), participants often asked clarifying questions from the expert panel via an on-line interface; and the reasons that participants provided individually and as groups for their votes were consistent with those addressed in discussions. In addition, the table observations showed that many participants considered and in some cases advocated reasons in support of their views on Option A or Option B that were not reported with the votes. Nonetheless, there was variation in the extent to which participants identified issues not addressed in the background material, in how directly they engaged one another's arguments, and how well they understood the material.

As for tracing citizen rationales, the ECAST team asked the following questions that NASA decision-makers wanted to know as they considered the results: Is it possible to trace why citizens provided the answers they did? Is it possible to see if their input is based on solid and adequate reasoning? In Table 4, the written notes from an ECAST table observer from an Arizona table that voted for Option A were highlighted for NASA managers and engineers to illustrate how citizens developed rationales and worked through misconceptions. It is clear that the participants carefully examined and read through the background information. The vignette helps establish that the group made a technically credible decision. Further, the individual written rationales on A, shown in Table 5, listed the potential for larger samples of asteroids to study and the removal of space debris as a potential side benefit. This illustrates that in combination with table observations, individual rationales provide more clarity on why an option was chosen. It is important to understand here that while this group did not vote in the direction that most groups voted, they did have a consistent logic for the choice they made that NASA personnel could use to reflect on their own decisions.

Table 4. Table Observer Notes on Option A.

At one of the four tables in Arizona that voted for Option A, several participants expressed their preference for "the bag" very early in the conversation. A great deal of attention was given to sorting through technical questions, most of which the participants resolved by consulting the background material and table cards. This group questioned the material that had been provided to them and they also questioned one another. Given the concerns in the video that the material to be retrieved via Option A might turn out to be a rubble pile, the group asked the NASA experts if this affected the value of the material. The response was that "There is nothing wrong with capturing a rubble pile. The astronauts would still be able to approach the captured rubble pile, so the crewed mission could still work either way. The composition of the asteroid could be more or less interesting for science." This reinforced the participants' views that there were few downsides to Option A. As one participant noted upon receiving the expert response, "Well if they don't know the value of it then it's not a risk." The conversation then turned to the nature of the risk described in the background material, with one participant noting that "it says there is a possibility the asteroid would have to be de-spinned, and engineers don't know how to figure that one out," but another immediately respond that "it said it was more of an

engineering challenge" and went on to argue that she took this to mean that it was a challenge that could likely be overcome. This attention to detail and shared problem-solving was evident throughout the discussion. While there were some disagreements between participants on facts and arguments, both pros and cons of Option B were discussed and all participants expressed their support for Option A when the facilitator polled them.

Table 4. Combined Group and Individual Written Justifications for Table 4.

Table/Participant	**Option A**	**Most Important Factors/Primary Motivation**
4	1	Scenario A More material, space junk, side benefits
4-1	1	Seems more probable
4-2	1	It can pick up space junk as well as asteroids. It can get bigger asteroids, too.
4-3		Cost and safety
4-4	1	Get a whole asteroid rather than a small piece of one. Practical application of also collecting space trash in orbit around Earth.
4-5	1	Larger sample for more research
4-6	1	Scenario A allows us to take a larger sample of the asteroids. A single boulder may not be indicative of the materials and properties of its host asteroid. An entire one lets us have a larger sample until we have a focused research goal.
4-7	1	Smaller boulder in option 2 can be from another boulder and not necessarily able to give us the information for the "big 1.. Also, love the idea of "cleaning" up the solar system.

Impact: NASA Use of Participatory Technology Assessment Data

A key contribution of the pTA was discussed in the last section: the results represent a public value map of what a more informed group of the public thinks about different aspects of the ARM mission, including perceptions about economic goals, technical risks and uncertainty. This is a contribution on its own, as it represents a synthesis of views that can be considered by decision-makers as they reflect on their own values. However, an additional contribution can follow from assessing how the results from this forum were used by NASA and to assess the results of the ultimate decision on ARM. Demonstrating a meaningful impact that resulted from the participant discussions can help serve as proof that the broader purposes of pTA are being achieved, empowering citizens that provide public value maps to aid decision-making, build individual capacity to make informed decisions, create a sense of public ownership, and develop a source of unique external technical input through a form of crowdsourcing.

Independent assessment of the importance of the NASA ECAST pTA to internal NASA decision-making processes is a challenge, as pre-decisional information surrounding government procurement decisions cannot be shared publicly. This means that sensitive details of the criteria for procurement decisions and the relative salience of items that fed into them cannot be fully discussed. Nonetheless, there are several ways to assess the results of the decision: official NASA statements on the results from the citizen forum; assessing the formal role of the pTA results in the decision; and self-reporting from NASA officials, whom are co-authors here, as to the value of the results.

Given that NASA is a heterogeneous organization with different managers and personnel that each have different opinions, official agency statements are often the best way to assess what NASA's views are. Such statements are developed by program staff and signed off on by multiple chains of management. In a formal press release discussing the pTA results, NASA claimed: "This innovative approach exposes NASA, through a third party, to new views the agency might otherwise not have access to – opinions from Americans interested in the future of NASA exploration and our journey to Mars… Study participants expressed nuanced and informed preferences about the options… NASA decision makers have evaluated the perspectives uncovered through this innovative approach and will consider the data, and this new approach to informed public participation in America's space program, as we continue our journey to Mars."[49] This reflects overall a sense of appreciation for the insights provided by the citizens, viewing the results as 'nuanced and informed preferences.' This level of recognition is a first for a government agency using pTA results.

Furthermore, the results of the citizen forum were used as information in part of the decision[50]. This itself is likely a first for a major government activity: senior management time is a precious commodity inside of an agency, and that the ARM program management team chose to share results more broadly in the final agency decision meeting is significant. Public engagement (or 'communications') products are not typically discussed in an acquisition context, which highlights that this pTA was used as a decision support tool.

We can also provide insight on how NASA managers considered the pTA data during their decision-making process without sharing pre-decisional information. The general preference of the participants (Option B) did align with NASA's eventual choice, and some of the core rationales and values expressed by the public helped affirm NASA managers' sense of their own values as they approached the decision. We felt that the forum was a step in the right direction in terms of developing stronger linkages between decision makers and public engagements.

We can also give insight on how the NASA team interpreted the results and presented them to higher levels of management inside of NASA. NASA focused on the ARM results earlier than the rest of the deliberation results because they wanted to review them before making a final decision about Option A versus Option B. In fact, NASA asked ECAST to accelerate the forum dates to be able to have the data in advance of making their decisions. The preliminary results from the forums included the voting results, participant views of the process through a post-survey, and a rough qualitative analysis of participant rationales. The second author of the paper (Pirtle) presented the results to NASA management as discussed above, and then provided ECAST feedback. Discussions within NASA management ranged from whether the background material biased participant preferences toward Option B, whether differences in facilitator quality between Arizona and Massachusetts affected results, whether the overall framing of the forum may have biased the participant responses, and whether discussion at the event of 'de-spinning' as a risk for Option A, which experts find to be surmountable, biased the answers between Option A and B. In response, ECAST discussed challenges with the deliberation and facilitation process and presented opportunities to improve on the process. ECAST worked up a further analysis to answer questions concerning the effects of overall forum framing on participant choices (did the framing bias participants towards Option B), participant ability to overcome misconceptions, inconsistencies in forum implementation (why did the Arizona forum have groups voting for Option A, but not Massachusetts), and the processes by which participant's reasoned out their choices. Based on this analysis, specific threats of bias, such as the overall framing of the forum and possible misconceptions about de-spinning, were deemed not to be a major threat to reliability as they were not commonly cited in the written rationales. However, uncertainty remained, and NASA analysts did not perceive the final vote percentages for Options A and B as being definitive of what an informed public would prefer.

In the end, the iterative dialog between ECAST and NASA did generate a rough public value map that highlighted the socio-technical complexity that lay citizens introduce into an assessment of emerging technology that NASA managers could reflect on in relation to their decision about Option A versus B. Once questions about the legitimacy of the "Informing NASA's Asteroid Initiative" forums were addressed, it did allow internal NASA briefings to be focused more on the diverse and at times conflicting values expressed in different participant rationales. During meetings, NASA managers gave more attention to qualitative results that showed value statements about different participant perceptions of the two choices than on quantitative results. The nature of the citizens' input was diverse, including some formal rankings of risk, a prioritization of possible goals for the mission, as well as, some discussion of schedule priorities.[51] Many of the written rationales incorporated the values and goals of the citizens, while others provided technical opinions about risk or economic value. Common participant rationales provided in the forums included potential uses for Mars exploration, more precise control of asteroids, adaptability to different types of missions, and developing improved planetary defense techniques (Option B), obtaining a larger asteroid sample for economic and research purposes, and the ability to remove orbital debris (Option A). This list of common rationales was a central point in NASA's internal briefings on the forum results. Internal briefings said that these rationales could be useable by management to help reflect on their own values and goals for the mission. While managers reviewed both quantitative and qualitative results, the results themselves were not used to directly decide which approach to ARM should be pursued. However, the combination of quantitative and qualitative results helped managers consider statements written by a broader group, better positioning themselves to consider what would benefit the public at large.

Theoretical Insights and Caveats

Separate from the practical impact, there are several aspects of the pTA results that provide insight on the complexity of pTA and on the nature of how results are used. The first theoretical comment is the amount of co-learning that happened among NASA officials and the ECAST personnel during the process. The presentation of results was an iterative process of several presentations, followed up with questions from NASA, several rounds of analysis, a couple preliminary reports, and then a final report.[52] As a consequence, NASA and ECAST had significant dialogue and interaction prior to December that involved discussions about the reliability of the results and exploring possible biases in participant responses. This high level of interaction was not anticipated by either ECAST or NASA, as neither had experienced a partnership of this nature before. In hindsight, we realized this exercise became a co-learning process about how to best integrate results into NASA's decision-making process. It took several rounds of discussions for each partner to understand what could be done with the results and accompanying data.

Not being familiar with pTA deliberations, NASA personnel initially used this exchange as an opportunity to better understand how deliberations work and the extent that lay citizens can assimilate technical information. While on the surface this line of questioning privileges the deficit model of public understanding of science,[53] it is a necessary step in building trust between the deliberation process and decision-makers. It builds the foundation on a proximal level that allows a deeper reflection on the rationales and values of participants, and on a more ultimate level that firms up linkages between public engagement and decision-making processes.[54] In essence, it is a step toward "opening up" conversations about the future direction of emerging space technologies.[55] The process became an opportunity to experiment with making social values "useable" for decision-makers.[56] This iterative dialogue/co-learning may have been necessary to build trust on the NASA side of the dialogue.

Projects such as the NASA pTA exercise, offer excellent opportunities to study novel public input mechanisms. Future pTA partnerships with government agencies should adopt a rigorous assessment apparatus designed to understand the nature of institutional change associated with pTA and how deliberation results are used in decision making. Emery et al's[57] observations about developing meaningful linkages between public engagement exercises and decision-makers is very apt in hindsight of this experiment.

> What is missing is an audit of the final decision-making process – a process which often involves last-minute modifications and compromises that are not reported. Such an audit would shed light on how decisions are made, including under what circumstances evidence is or is not taken up and used. This offers greater potential for identifying more concrete relationships between PE practices and policy. (p. 441).

However, there are real limits to what pre-decisional information can be shared, especially in environments with multiple stakeholders. While most scholars of public engagement describe a successful integration of deliberation results as having post-analysis that shows the influence of a pTA events,[58] which this partnership did not do, reflecting on the experimental relationship between ECAST and NASA helps us understand ways to better integrate data into decision-making and some of the challenges of doing so.

Conclusion

In sum, this proof of concept study informs an engineering decision using public deliberation. This paper reports on an interesting episode in the history of NASA and the Asteroid Redirect Mission: it marks the first time that a NASA mission has had a structured participatory element involved in making strategic and technical decisions. Simply considering feedback from a representative public in early mission planning is unique for NASA and is rare within the broader U.S. government. Furthermore, the pTA results achieved the experiment's goal of soliciting myriad diverse views that NASA is not traditionally exposed to. It was of value to managers to consider these results and the effort suggests how engineering decisions benefit from having structured and deliberated public input. As future R&D managers strive to meet the needs of the public, being able to reflect on structured and informed public views can significantly help managers bring forward proposals that will best deliver what society wants.[59]

To inform the practice of pTA, the iterative co-learning observed in our experiment helps indicate the amount of effort that may be needed for future pTAs to be useful when engaging with government partners. New ground was explored with this pTA effort, as it may be unique in the level of technical depth explored by citizens, as well as, the pTA being tied to a tangible decision (the ARM down-select). Mapping out the values involved by the public is a useful avenue for proactively drawing in the public to inform future engineering decisions.

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Notes

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1. The opinions and views expressed in this paper do not necessarily reflect the opinions of the United States government, NASA or of the institutional affiliations of the authors.
2. Science, Technology & Society Programs, University of Maryland, College Park, MD, dtomblin@umd.edu.
3. National Aeronautics and Space Administration, Headquarters, Washington DC.
4. Consortium for Science Policy Outcomes, DC Office, Arizona State University, Washington, DC.
5. Museum of Science, Boston, MA.

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6. Valador, Herndon, VA.
7. Science, Technology and Society, Pomona College, Claremont, CA.
8. Center for Science, Technology, Medicine and Society, University of California Berkeley, Berkeley, CA.
9. National Aeronautics and Space Administration, Headquarters, Washington DC.
10. Consortium for Science Policy Outcomes, Arizona State University, Tempe, AZ.
11. National Aeronautics and Space Administration, Headquarters, Washington DC.
12. National Aeronautics and Space Administration, Headquarters, Washington DC.
13. Consortium for Science Policy Outcomes, DC Office, Arizona State University, Washington, DC.
14. Consortium for Science Policy Outcomes, Arizona State University, Tempe, AZ.
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42. For more info on gravity tractor technology, see Tomblin – Full report in note 35.
43. In March 2015, NASA announced that it chose Option B for the Asteroid Redirect Mission (See: http://www.nasa.gov/feature/innovative-study-supports-asteroid-initiative-journey-to-mars (accessed October 10, 2016).

Since this paper went into peer review, the NASA President's Budget Request proposed to cancel the Asteroid Redirect Mission and the program is currently closing out its activities. Much of the work of ARM will continue to be used in future NASA programs.

44. Different voting patterns did occur between the Phoenix and Boston sites, but at both sites a significant majority chose Option B (significantly more participants chose Option A at the Phoenix site than in Boston). However, since the main goal of the experiment, and this article, was to explore participant values and rationales for their choices rather than an affirmation of one technological choice over another, we don't explore here why this happened (see Tomblin et al Full report in note 35 for potential explanations).
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50. The timing of the ARM decision and the pTA results are described here, though it is not essential to the final results. As discussed, during 2014 and the first part of 2015, NASA was actively considering a downselect to focus on one of two options to achieve ARM: Option A, to capture a 10m diameter asteroid, direct it to the moon and then send astronauts to do research on it, and Option B, to capture a 3-5m diameter boulder from the surface of a much larger asteroid, direct it to the moon, and then send astronauts to it. A NASA analysis meeting on the two ARM options was planned for December 16th, 2014 to help inform the decision, at which point NASA decided that more time and analysis was needed to make the decision. NASA announced the final downselect decision in March 2015: the agency selected Option B as its chosen approach for implementing the mission (see note 44). NASA received results in Dec 2014, made final decision in March 2015

    During this time frame, the pTA deliberations, which had been held in November 2014, was considered by NASA management during ARM downselect meetings. On December 1, 2014, soon after the forums, ECAST provided NASA with an interim report summarizing the ARM pTA results, including an earlier draft of some of the analysis above. Prior to the downselect decision, NASA analysts assessed the data and briefed a summary of the results to NASA ARM downselect management team on December 10, 2014. Internal briefing discussions prior to the December 16 analysis meeting focused on the diversity of values that participants discussed in their voting rationales and what they saw as the goals for ARM (Table 2).
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