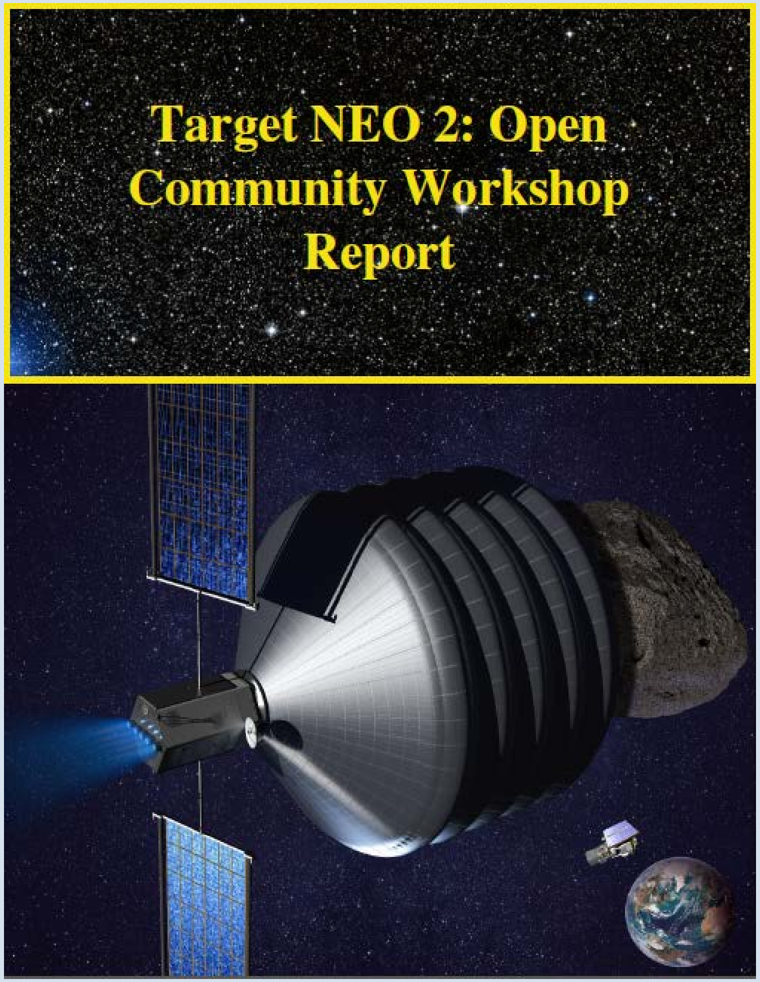
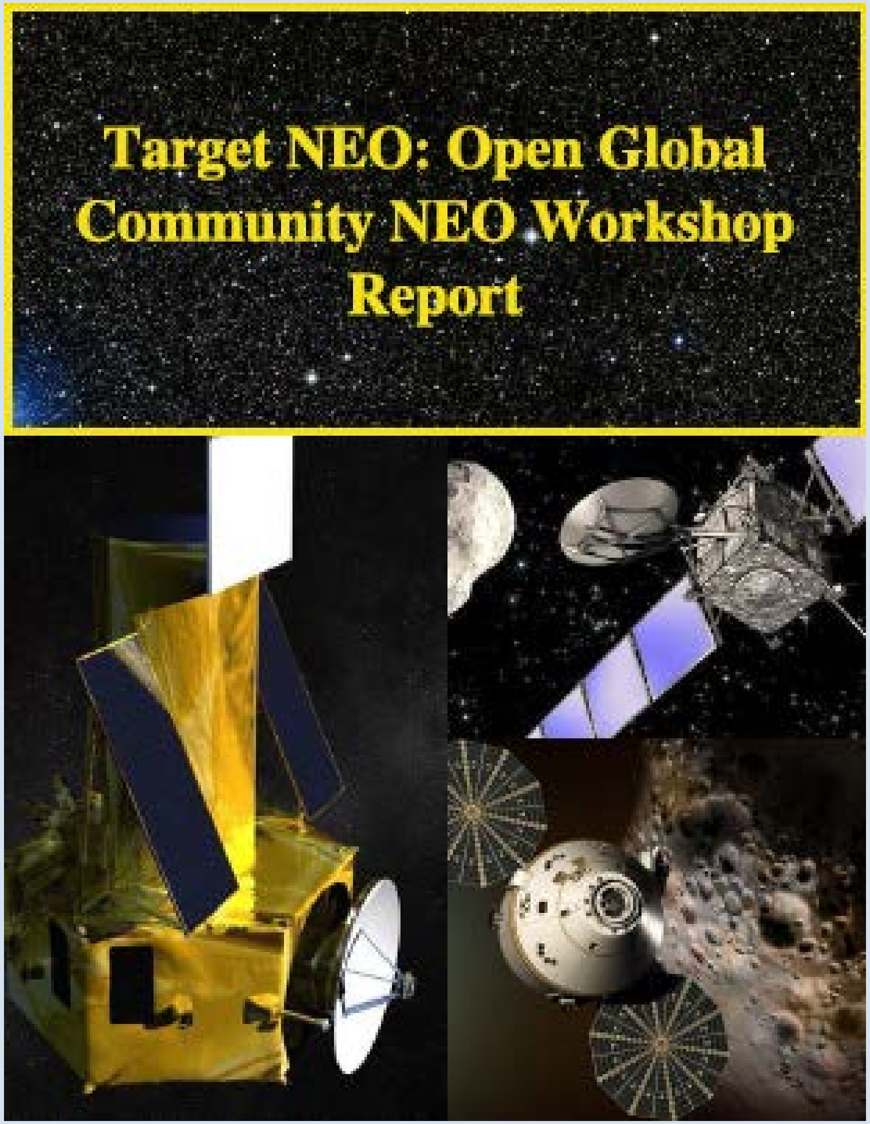


Target NEO 2 Workshop Summary

Rich Dissly, Ball Aerospace
Cheryl Reed, APL
And Target NEO 2 Co-Chairs

Previously…

- Target NEO (1) Workshop was in Feb, 2011 at GWU
- Motivated at the time by the need to find additional accessible NEA targets for human exploration
- Conclusion at the time was that a space-based survey was needed to meet the goal of sending humans to an asteroid by 2025
    - Needed to find significantly more targets quickly to enable robust mission planning
- TN1 Workshop presentations and final report are on the Target NEO website (targetneo.jhuapl.edu)



Overview of Target NEO 2 Workshop

- NASA's *Asteroid Initiative* has prompted much community discussion on both the science value and the technical and programmatic challenges involved with this campaign. Specifically, much of this discussion has centered around the prospect of an asteroid redirect mission.

- The **Target NEO 2 Workshop** was a community-driven activity to discuss these challenges, and to provide objective technical input from experts in fields pertinent to robotic and human NEO exploration, to identify areas of potential risk and help inform ARRM (Asteroid Robotic Redirect Mission) formulation. It was structured around a series of technical and programmatic topics, and was not a forum for broader policy discussions.

- The Workshop was held July 9, 2013, at the National Academy of Sciences Auditorium, in Washington, DC. In attendance were over 140 people in person, and over two dozen via WebEx, representing academia, NASA, industry, and the international space exploration community.

- The Workshop presentations and discussion were focused around a few key questions:
  - *What are the technical challenges involved and what new capabilities are needed for ARRM?*
  - *What technical information is still needed?*
  - *Are there any alternative approaches?*

- All presentations from workshop are uploaded to website: http://targetneo.jhuapl.edu

- Draft of **Final Report** is also on the website, open for public comment until 10/14

Target NEO 2 Workshop Agenda

Session 1: Update to Flexible Path Vision

- *Overview of NASA's New Asteroid Initiative* (Bill Gerstenmaier, NASA HQ, AA HEOMD)
- *NRC Human Exploration Study Update* (Michael Maloney, SSB)
- *Global Exploration Roadmap Update, ISECG Perspective* (Kathy Laurini, NASA HQ)

Co-chairs: Doug Stetson (Independent) & Cheryl Reed (APL)

Session 2: The Small (<10 meters) NEA Population

- *Population Estimates of Small NEAs* (Al Harris, More Data!, Inc.)
- *Small NEA Characteristics* (Andy Rivkin, APL)
- *Modeling Capabilities and Uncertainties* (Bill Bottke, SwRI)
- *Estimated ARM Candidate Target Population and Projected Discovery rate of ARM Candidates* (Paul Chodas, JPL)

Co-chairs: Mark Sykes (PSI) & Dan Britt (UCF)

Session 3: Finding Small NEAs – Current Capabilities and Gaps

- *Tutorial on Process of Finding Small NEAs* (Tim Spahr, MPC)
- *Follow-up Characterization Needs and Issues* (Lance Benner, JPL)
- *Existing and Near-Term Ground-Based Capabilities and Gaps* (Steve Larson, U of Arizona)
- *Discovery Process for Finding ARM Targets Using PS2 and Atlas* (Eva Schunova, U of Hawaii)
- *Existing and Near-Term Space-Based Capabilities and Gaps* (Amy Mainzer, JPL)

Co-chairs: Paul Abell (JSC) & Rich Dissly (Ball)

Session 4: Small NEA Mission Design Challenges

- *End-to-End Mission Design Trajectory Optimization* (Damon Landau, JPL)
- *Proximity Operations and Characterization/Nav/Control* (Steve Broschart, JPL)
- *Docking, Grappling, Capture, Control, and Alternative Approaches* (Carlos Roithmayr, LaRC)
- *Maintaining a Safe, Stable, and Human Accessible Parking Orbit* (Dave Folta, GSFC)
- Defining Key Technology Requirements (John Dankanich, MSFC)

Co-chairs: Brent Barbee (GSFC) & Steve Chesley (JPL)

Session 5: Technical Value of ARM, Panel Discussion

Panel

- Gentry Lee, JPL
- Doug Cooke, AA NASA (Retired)
- Tom Jones (FIHMC, former astronaut)
- Jim Bell (ASU)

Co-chairs: Dan Mazanek (LaRC) & Faith Vilas (PSI)

Session 6: Session Summaries and NASA Response

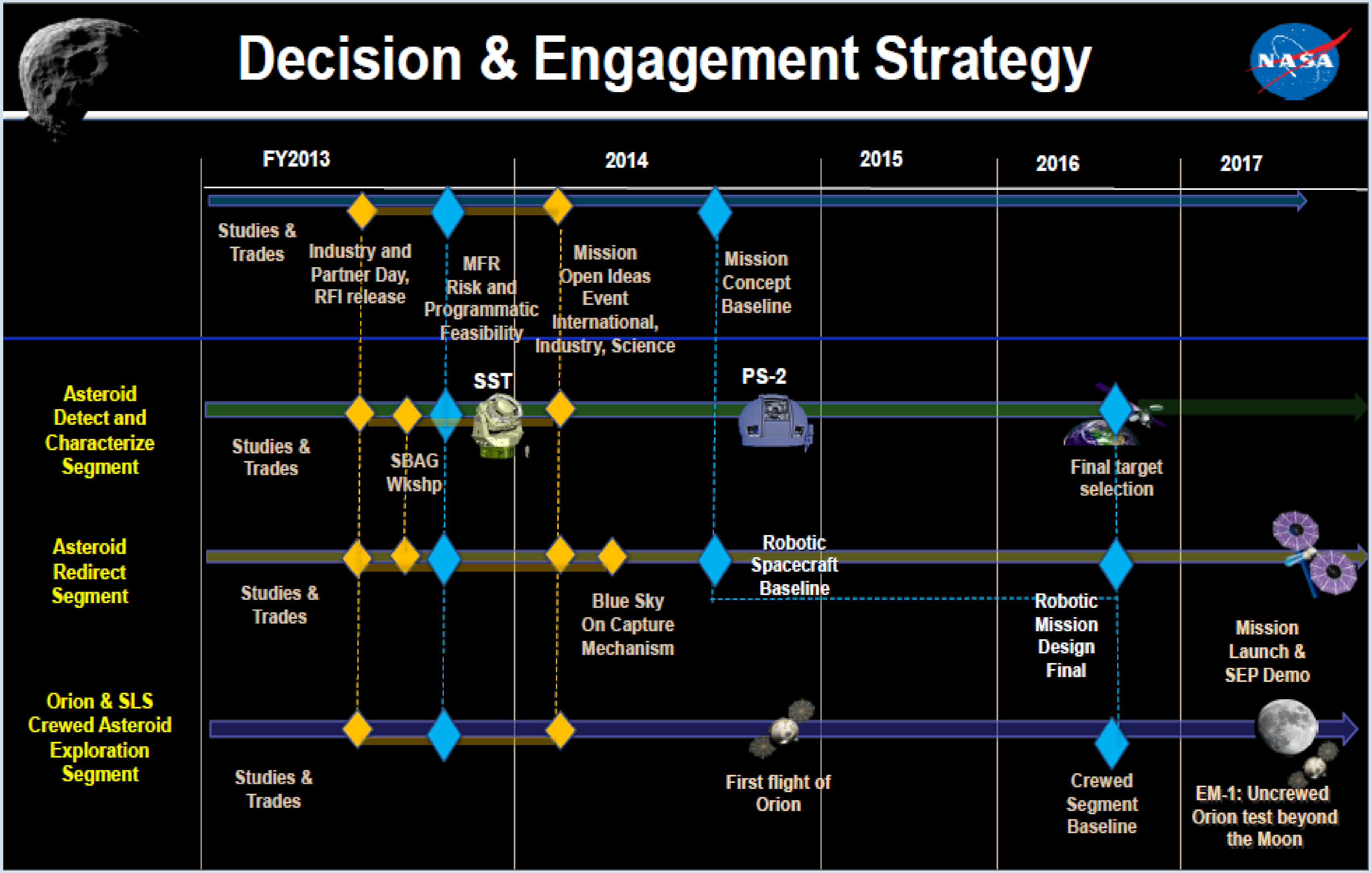
- Session 1-5 Co-Chairs
- Jim Green, NASA HQ
- Greg Williams, NASA HQ

Session 1: Update to Flexible Path Vision

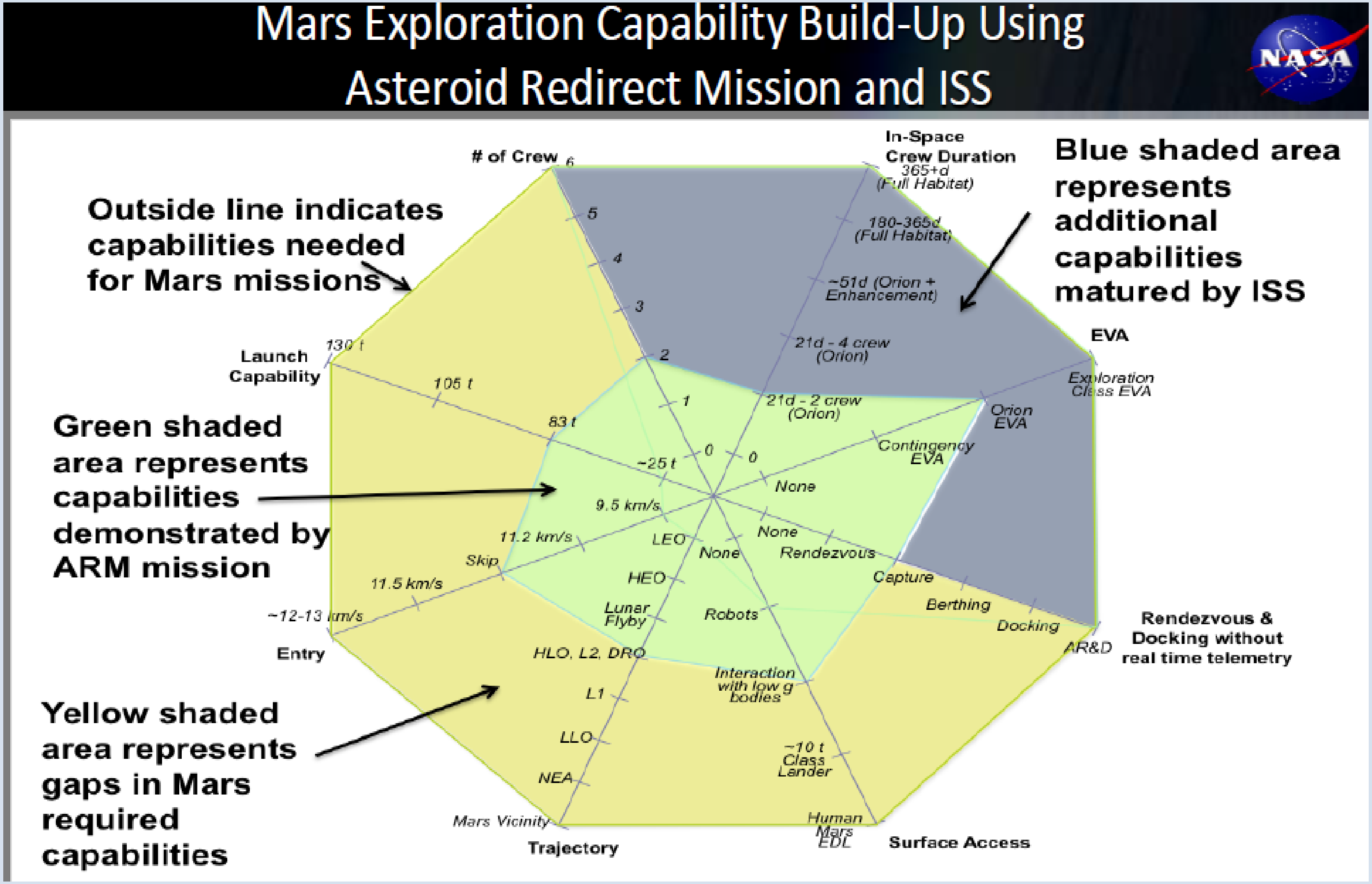
- *Overview of NASA's New Asteroid Initiative* (Bill Gerstenmaier, NASA HQ, AA HEOMD)
- *NRC Human Exploration Study Update* (Michael Maloney, SSB)
- *Global Exploration Roadmap Update, ISECG Perspective* (Kathy Laurini, NASA HQ)

Co-chairs: Doug Stetson (Independent) and Cheryl Reed (APL)

Notional schedule from Gerstenmaier presentation



Feed-Forward from Gerstenmaier presentation



Session 1 Summary

Gerstenmaier:

- ARM capability driven towards an ultimate Mars destination. Leverages existing technology investments
- 2016 final target selection, goal for 2017 launch to enable Mars mission in 2030's
- Will likely need to build the spacecraft prior to a target selection. This would likely drive a spacecraft overdesign to support multiple mission scenarios.
- The differences of the missions are so extreme (free-space target, boulder on a rubble-pile), it is acknowledged that a decision needs to be made "soon" as to which mission scenario will be pursued.
- Potential for higher costs, including a need for a larger, more costly LV given the inability to optimize to a point design.
- Key questions:
  - What is process by which these mission and spacecraft requirements will be developed? Note of extreme caution: Well-known that a lack of clear and specified requirements is the top culprit for driving-up (uncontrollable) mission cost.
  - Need to define mission success criteria. Doubtful that not bringing an asteroid back would be seen as an acceptable success criteria.
  - Need to define a realistic cost cap (which establishes a cost uncertainty range) and schedule.

Session 1 Summary (cont'd)

Maloney:

- An overview of studies by NRC/NAS to assess human exploration over last few decades was provided. A current study focuses on future relevance and focus of human space (what it should and should not be). This report will be released in ~Feb 2014.

Laurini:

- An overview of the Global Exploration Roadmap (GER) update was provided, and how ARM could fit into this architecture in an international cooperation construct. Noted that international collaboration and contribution is key to a robust and sustained human exploration program.
- Discussion of specific international cooperation on ARM has not yet occurred, however, it is likely that any contribution would come from existing partner efforts due to the highly compressed ARM implementation schedule.

Session 2: The Small (<10 meters) NEA Population

- *Population Estimates of Small NEAs* (Al Harris, More Data!)
- *Small NEA Characteristics* (Andy Rivkin, APL)
- *Modeling Capabilities and Uncertainties* (Bill Bottke, SwRI)
- *Estimated ARM Candidate Target Population and Projected Discovery rate of ARM Candidates* (Paul Chodas, JPL)

Co-chairs: Mark Sykes & Dan Britt

From Chodas presentation

Characteristics of ARRM Target Candidates

Characteristic	Reference Value
Orbit: $V_{infinity}$ relative to Earth	*< 2 km/s desired; upper bound ~2.6 km/s*
Orbit: Natural return to Earth	*Orbit-to-orbit distance (MOID) < ~0.03 au,* *Natural return to Earth in early 2020s (or 2020-2026)* *("Return" means close approach within ~0.3 au)*
Mass	*<1,000 metric tons* *(Upper bound varies according to $V_{infinity}$)*
Rotation State	*Spin period > 0.5 min* *Non-Principal-Axis rotation is assumed to be likely*
Size and Aspect Ratio	*4 m < mean diameter < 10 m (roughly, 27 < H < 31)* *Upper limit on max dimension: ~14 m* *Aspect ratio < 2:1*
Spectral Class	*Known Type preferred, but not required* *(C-type with hydrated minerals desired)*

From Chodas presentation

Characteristics of Current ARM Potential Candidates

Characteristic	Reference Value	2009 BD	2011 MD	2013 EC20	2008 HU4	2007 UN12	2010 UE51
Orbit Confidence	*OCC < 4*	*Excellent*	*Good*	*Recoverable*	*Recoverable*	*Recoverable*	*Good*
Orbit: Vinfinity (km/s)	*< 2 (< 2.6 req.)*	*0.7*	*0.9*	*2.6*	*0.5*	*1.2*	*1.2*
Orbit: Natural return year	*Early 2020s (2020-26)*	*2023*	*2024*	*2020*	*2026*	*2020*	*2023*
Size (m)	*< 10 and > 4*	*< 8 [1]*	*< 30 [4]*	*2-3 [6]*	*< 28 [4]*	*< 22 [4]*	*< 27 [4]*
Mass (t)	*< 1000*	*< 500 [2]*	*< 50,000 [5]*	*< 50*	*< 40,000 [5]*	*< 20,000 [5]*	*< 36,000 [5]*
Spin Rate (rpm)	*< 2*	*< 0.01 [3]*	*0.1 [3]*	*< 2 [6]*	*Unknown*	*Unknown*	*Unknown*
Spectral Class	*Known (C preferred)*	*Unknown*	*Unknown*	*L or Xe*	*Unknown*	*Unknown*	*Unknown*
Next Observation Opportunity	*A=Astrometric O=Optical IR=Infrared R=Radar*	*2013-Oct: IR*	*2014: IR?*	*2013-Aug: A?*	*2016-Apr: A, O?, R*	*None*	*2014: IR??*

Notes: [1] NEOWISE stacked non-detection; [2] Upper bound density: 1.5 g/cc from Micheli et al.; [3] Magdalena Ridge lightcurve; [4] Lower bound on abs. mag. and lower bound albedo of 3%; [5] Upper bound density of 3.5 g/cc; [6] Arecibo radar.

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Session 2 Summary

ARM Target Characteristics (Chodas)

- Orbit: $V_{infinity}$ relative to Earth < 2 km/s desired, <2.6 km/s required.
- Orbit: Natural return to Earth. Orbit-to-orbit distance (MOID) < 0.03 AU, Natural return to Earth in early 2020s (2020-2026) (i.e., close approach within 0.3 AU)
- Mass: <1,000 metric tons (upper bound varies according to $V_{infinity}$)
- Rotation State: Spin period > 0.5 min. Upper bound on angular momentum: ~$1x10^6$ kg-m^2/s. Non-Principal-Axis rotation can be accommodated
- Size and Aspect Ratio: 4 m < mean diameter < 10 m (roughly, 27 < H < 31). Upper limit on max dimension: ~15 m. Aspect ratio < 2:1
- Spectral Class: Known Type (C-type with hydrated minerals desired)

Session 2 Summary (cont'd)

Projected Discovery Rate of ARM Candidates (Chodas)

- The ARM candidate discovery rate will almost certainly increase due to enhancements to existing surveys and new surveys coming online.
- Current detection of targets meeting ARM dynamical and magnitude constraints is ~2.8/year. Expanding existing and new ground-based facilities may double this.
- With at least another 3-4 years to accumulate ARM candidate discoveries, at least ~15 more ARM candidates are expected to be discovered; favorable mission design trajectories should be available for at least half of these.
    - *Fraction of ARM candidates that meet size/mass requirements is not known.*

Session 2 Summary (cont'd)

ARM Population Uncertainties and Options

- Most Asteroid Redirect Mission (ARM) Candidates, objects on very Earth-like orbits, are from the main asteroid belt (Bottke).
- There are probably many thousands to many tens of thousands of ARM Candidates.
- Our existing NEO models, developed for large NEOs, may break down for small NEOs.
- Estimates suggest our NEO models may be missing as much as a factor of 8-10 of the ARM Candidate population.
  - Possible sources of ultra-low v_∞ NEAs are Lunar ejecta (most), space debris (some), Main-belt asteroids (almost none), Mars ejecta (almost none).
- Minimoons are NEOs that have been temporarily captured in the Earth-Moon system. We argue they provide superior targets for future human missions.
- A minimoon mission may allow NASA astronauts to reach an NEO by 2025 at lower cost and risk than other prospective missions.

Session 2 Summary (cont'd)

Uncertainties of Potential ARM Target Physical Characteristics

- Albedo uncertainties for a given brightness lead to factor of ~3 uncertainty in size → factor of ~25-30 in mass. Albedo/size measurements are imperative. (Rivkin)
- Range of likely-seeming porosities from zero (*if* monolith) to 50% (if like larger asteroids, high end of TC3 estimate) → Densities from ~1 g/cm^3 - ~3 g/cm^3 → another factor of 3 in mass (*irreducible prior to S/C visit?*). (Rivkin)
- Great uncertainty in understanding overall population composition because of (unconstrained?) fraction of low albedo X-complex asteroids. Expect >~5% of NEOs to have hydrated minerals. (Rivkin)
- Rotation rates likely < 5 minutes (Rivkin). Many small objects are tumblers (Harris).
- Regolith cohesion can result in a 10m rubble rapidly rotating < 0.5 RPM with >mm grains on the surface (Scheeres & Sanchez).

Session 2 Summary (cont'd)

Uncertainties of Potential ARM Target Physical Characteristics

- In choosing a very low v_∞ target, you need to have very good physical characterization of the object if you want to be sure you aren't bringing a piece of the moon back to its home, or even an old rocket body. (Harris)

- Size/mass determinations are essential as it can easily push a dynamic/magnitude compliant candidate beyond the ARM target requirement range.

- Is it possible to adequately characterize all potential ARM targets in the time period after their discovery?

- A rapidly rotating cohesive rubble pile may represent a source of risk against interacting with the surface (intentionally or unintentionally).

Session 2 - Summary of Key Findings

- The extent to which the population of ARRM targets derives from the main asteroid belt is uncertain. It is possible they may be dominated by lunar ejecta, and include spacecraft and rocket bodies. These should be distinguishable by remote observations.

- Several objects per year are discovered that qualify as potential ARRM targets and this number may double as new survey assets become available. The fraction of these objects that satisfy ARRM target requirements, however, is uncertain.

- Uncertainty in size and mass translates to smaller nominal size to ensure ARRM target requirements are met which, in turn, can reduce the discovery rate of potential targets. Accurate characterization is critical.

- Radar and other ground-based and space-based telescope assets exist that can greatly reduce the uncertainty in potential target size, mass and rotation state. Most potential targets should be available to these assets for study.

- Some objects, including rapidly rotating objects, may be rubble piles held together by Van der Waals forces. Such objects may represent a significant risk to an ARRM spacecraft. It may not be possible to completely characterize the details of physical structure through ground- or space-based observations.

Session 3 - Finding Small NEAs Current Capabilities and Gaps

- *Tutorial on Process of Finding Small NEAs* (Tim Spahr, MPC)
- *Follow-up Characterization Needs and Issues* (Lance Benner, JPL)
- *Existing and Near-Term Ground-Based Capabilities and Gaps* (Steve Larson, U of Arizona)
- *Discovery Process for Finding ARM Targets Using PS2 and Atlas* (Eva Schunova, U of Hawaii)
- *Existing and Near-Term Space-Based Capabilities and Gaps* (Amy Mainzer, JPL)

Co-chairs: Paul Abell & Rich Dissly

From Chodas presentation

Options for Increasing the ARM Candidate Discovery Rate

	Facility	V_{lim}	FOV (sqdeg)	In Work or Potential Improvements	Date	Notional ARM Discoveries per Year*	Recommendation
Current	Catalina Sky Survey			•Increase ML field of view by 4X	Late 2013	2-3	Encourage
	Mt. Bigelow	19.5	8	•Increase MB FOV x 2.5	Late 2014	1-2	Accelerate
	Mt. Lemmon	21.5	1.2	•Retune observation cadence	Mid 2014	3-5	Accelerate
	Pan-STARRS 1	22.5	7	•Improve Software to capture moving & trailed objects (happening now)	Mar. 2013	1-2	Encourage
				•Increase time in NEO mode (from current 11% to 50%)	Mid 2013	2-6	Request more time
				•Could be dedicated to NEA detection	Early 2014	4-12	Request 100%
Future	Pan-STARRS 2	23	7	•Could be dedicated to NEA detection	Mid 2014	5-15	Fund completion & camera upgrade
	ATLAS	20	40-80	•View entire sky every night x 2 sites	Late 2014	8-16	Accelerate completion
	DARPA SST	22+	6	•Minor software mods	Apr. 2013	2-6	Investigate scheduling NEO time
	Palomar Transient Factory (PTF)	21	7	•Improve Software to capture streaked objects	Mid 2013	1-2	Schedule time in NEO mode and upgrade IPP
	PTF-2 (ZTF)	21	35	•5 x FOV of PTF	Late 2014	3-10	Join partnership and accelerate completion

**Discoveries per year that meet ARM's rough size and orbit criteria for retrieval.* *V_{lim} = limiting magnitude*
N.B. Discoveries are not additive. There will be duplications of detections, particularly in the optimistic scenarios. Predictions for future discovery rates are based on extrapolated coverage and cadence.

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Session 3 Summary

- In the short time frame needed for ARRM, ground based assets offer the best opportunity to increase the viable target set
  - Several ground based assets are being upgraded/developed in time to increase the number of possible targets for ARM : CSS, PS2, and ATLAS are all likely to detect multiple objects/year in the ARRM size range
- Current and near-term space-based assets are better suited to follow-up characterization (IR obs) rather than detection of a large number of small objects
- Very limited time for follow up (few days for optical/IR, radar) – but low ΔV objects may offer a longer characterization window
- Size uncertainty by visible observations alone can be a factor of 2-3. This propagates into a much larger uncertainty in target volume, mass. IR or radar follow-up critical to reducing this uncertainty

Session 3 Summary (cont'd)

- Follow-up by ground based assets is very important to close an orbit in the short time available for small targets; most very faint objects currently "lost"
- Many follow-up limitations are organizational rather than technical
  - o Clearing house for follow-up observations at time of discovery, more rapid radiation clearance recommended as key improvements
- Simple upgrades and continued support to both Goldstone and Arecibo are important to support this as a NEA characterization asset
- Determining if a NEA has few meter-class boulders on the surface cannot be done remotely by IR, and limited with radar observations
- Detection of new, small objects by amateurs highly unlikely; the low-hanging fruit has been found.
  - o But skilled amateurs still very important for follow-up, characterization of already discovered targets.

Session 3 - Summary of Key Findings

- The set of potential targets for the ARRM is not yet robust. Additional targets are needed to ensure that a good subset meet the selection criteria.
- Ground-based assets are the only realistic opportunity to substantially increase the number of candidates in the near-term. Proposed space-based resources will not be available in time to contribute to the mission for any launch dates prior to 2020.
- Once a potential target is identified, follow-up observations to refine knowledge of its orbit and to characterize its size, mass, and spin state are critical. This characterization process is presently ad hoc and needs a more deterministic approach. The time window for characterization is just a few days.
- Visible observations alone are not sufficient to completely characterize potential targets. Follow-up IR and/or radar observations are mandatory. Ground-based assets are very important in measuring the NEA's orbit in the short time available for tracking.
- A clearing house for follow-up radar observations at the time of discovery and a process enabling more rapid radar radiation clearance are recommended. Simple upgrades and continued support to both Goldstone and Arecibo are important to enable their continued use as NEA characterization assets.
- ***Finding remains from TN1 Workshop that a Space-Based NEA Survey is still needed***

Session 4 - Small NEA Mission Design Challenges

- *End-to-End Mission Design Trajectory Optimization* (Damon Landau, JPL)
- *Proximity Operations and Characterization/Nav/Control* (Steve Broschart, JPL)
- *Docking, Grappling, Capture, Control, and Alternative Approaches* (Carlos Roithmayr, LaRC)
- *Maintaining a Safe, Stable, and Human Accessible Parking Orbit* (Dave Folta, GSFC)
- Defining Key Technology Requirements (John Dankanich, MSFC)

Co-chairs: Brent Barbee & Steve Chesley

Session 4 Summary

- Mission Design (Landau)
  - Given a suitable target, it appears feasible to rendezvous with and return an entire near- Earth asteroid using technology that is or can be available in this decade.
    - 6 years, 8 t of propellant, & 40 kW SEP system can return a 500 t asteroid to Earth/Moon capture orbit
- Proximity Ops (Broschart)
  - Solar radiation pressure (SRP) would dominate the dynamics during most ARM phases
    - A station-keeping strategy more practical than orbiting
  - Operations require a careful balance of OD/maneuver turnover time and execution errors
    - Autonomy can be used to minimize turnover time, which allows for larger maneuver/model errors
- Capture (Roithmayr)
  - Capture/despin of principal axis rotators appears feasible
  - Hovering at low latitudes appears impractical for fast rotators (suggesting that matching rates with a fast tumbler is also infeasible)
- Parking Orbit (Folta)
  - Distant Retrograde Orbits provide suitable stability without station-keeping
  - Dynamical Systems Theory and associated flight experience should be leveraged
  - Human accessibility of DRO is comparable to other alternatives, e.g., Lagrange point orbits
- Driving Technology (Dankanich)
  - Key technology development needs: Propulsion, Power, ProxOps, Capture Mechanism
  - Mission requirements not fully formulated making technological targets poorly defined
  - Unclear if these technologies can be “ready” in time for 2018 launch

Session 4 Summary (cont'd)

Issues from Q&A Discussion

- Tumbling rotation requires careful study: flexible structure dynamics, shearing inside capture mechanism
- Target mass uncertainty creates challenges/risks
- Boulder vs. Complete asteroid capture trade
- Xenon production question will be asked often
- Schedule is aggressive in terms of technology and target set
- Should ARRM get a pass on standard TRL and development oversight applied to other missions?
- Quantify value to ARM of
    - Enlarging the pool of suitable targets to afford more flexibility
    - Small robotic precursor to close characterization risks

Session 4 - Summary of Key Findings

- Distant Retrograde Orbits (DROs) are the recommended destination location for ARRM because they are extremely stable and can be reached with relatively low propellant requirements.
- Several identified potential ARRM targets are of the proper size and follow trajectories that may permit their redirection to a DRO in the 2020s using a 40 kW SEP system.
- Rendezvous with and hovering over an NEA has been done during previous robotic spacecraft missions with ground control in the loop. However, achieving the necessary navigation accuracy for ARRM will almost surely require some level of autonomous position control.
- It appears feasible to match rates with a tumbling NEA. De-spinning a fast tumbler will be easier when it is rigidly connected to the spacecraft.
- The technologies identified for advancement via ARRM are largely to meet the goals of the Space Technology Mission Directorate (STMD) and are not truly required for mission. Many ARRM Level 1 requirements remain undefined and thus the technology requirements for ARRM are still immature.
- The critical propulsion system development schedule is extremely aggressive and probably not feasible for a 2017 launch.
- Options may exist to reduce mission risk and schedule risk through reliance on state of the art technical solutions. ARRM appears to offer return on investment comparable to past technology demonstration missions while assuming comparable risk for technology development and demonstration.
- Human access to the captured asteroid is available several times throughout the lunar cycle and DRO orbit period.

Session 5 - Technical Value of ARM, Panel Discussion

Panel

- Gentry Lee, JPL
- Doug Cooke, AA NASA (Retired)
- Tom Jones (FIHMC, former astronaut)
- Jim Bell (ASU)

Co-chairs: Dan Mazanek (LaRC) & Faith Vilas (PSI)

Session 5 Summary

Key points from remarks

- Many benefits, but lack of mission definition is a significant risk
  - Define range of acceptable target characteristics and mission parameters
  - Schedule is too aggressive when coupled with funding uncertainties
- ARM has the potential to be a unifying, cohesive endeavor across NASA directorates
- Possibly the only near-term “planetary surface” destination
  - Use experience gained to reduce design uncertainties for future human missions and gain more crew autonomy
  - Progresses human skills and experience in deep space
  - Opportunity to demonstrate NASA competence and risk management within tight budget times
- Space resources
  - Breaks the paradigm of relying completely on resources brought from Earth
  - Promotes commercial and international partnerships

Session 5 Summary (cont'd)

Additional issues from Q&A/Discussion

- ARM is exciting, but in these austere times, what is our opportunity threshold cost? Depends in part on where the money is coming from – needs to come from HEOMD.
- Cost compared to OSIRIS-REx (60 grams vs. many, many tons). Need to have a reasonable schedule or costs of mission will become excessive (2019 earliest with proper funding).
- Public perception is that this mission is much more than technology demonstration mission
  - NASA needs to set bold goals for itself and reasonable success criteria
  - Relevant also for general public especially in terms Mars exploration
- Is the ARM concept worth the risk to astronauts? Consensus of panelists was "yes."
- Duration of crewed visit to returned asteroid is not on the same order as a Mars mission, but stretches Orion capability and Deep Space Habitat shake out and advances fault protection for this mission given that no quick return is available. ISS missions significantly helps with the long duration.

Summary Points

- ARRM has the potential to be a unifying, cohesive endeavor across NASA directorates and may be the only way to fulfill NASA's goal of a human asteroid mission by 2025.
- Key aspects of ARRM remain undefined, resulting in lack of clear requirements and success criteria and the potential for high cost and schedule risk.
- ARRM requires multiple significant technology developments and a complex implementation that present significant schedule and cost risk
- The difficulty in discovering targets that can be fully characterized with existing observational assets presents a major schedule risk.
- Uncertainty in asteroid physical properties (size, mass, spin state, mechanical properties) translates to significant mission risk, and there is at present no comprehensive plan for the observations required to refine these properties.
- ARRM will have limited applicability to planetary defense due to the small size of the target NEA. However, it may provide some marginal benefit from the systems, capabilities, and operational experience that can be leveraged.
- A firm cost cap and realistic development schedule are required before the community can fully evaluate or endorse ARRM as a step in the exploration architecture.

Detailed Findings: Target Detection and Characterization

- The set of potential targets for ARRM is not yet robust. Additional targets are needed to ensure that a good subset meet mission selection criteria for size, spin state, and orbit, and to provide viable backup launch opportunities.
  - Ground-based assets offer the only realistic opportunity to substantially increase the number of candidates within the current development schedule of a launch in 2017-18. Planned observatory upgrades/additions need to be realized.
  - A Discovery-class infrared space-based observatory (e.g., NEOCam or Sentinel) may make significant contributions to the number of candidate targets; however, such an asset could not achieve operational status until at least 2018.
- Follow-up observations to refine target orbits and to characterize size, mass, and spin state are critical to lower the uncertainty of these parameters for mission design, and need a more deterministic approach.
  - Follow-up visible, IR and radar observations are mandatory to reduce trajectory, size, mass, and spin state uncertainty in potential targets.
  - The current follow-up approach is too ad hoc; stronger follow-up procedures with identified assets are needed.
  - In addition to radar, a precursor mission may be needed to sufficiently characterize the target to lower mission risk to an acceptable level
- Uncertainties in the ARRM target population and the difficulty in discovering viable targets that can be fully characterized translates to significant schedule risk. It is not clear that a robust target set can be generated to meet the current ARRM schedule of a launch in 2017-18.
- There is a distinct possibility that some small, rapidly rotating asteroids may be rubble piles. For such objects, the forces holding them together may be quite small. Interaction with such an object during capture may represent a risk.

Detailed Findings: Technical Readiness of ARRM

- The key technology needs for ARRM include propulsion, power, proximity operations, and the capture mechanism. The lack of fully formulated mission requirements makes the technology development targets poorly defined. It is therefore unclear whether the needed technologies can be ready in time for a 2017-18 launch.
  - Traditional technology development practices (e.g., incremental advancement of TRL) and associated oversight may not be compatible with such an aggressive schedule. This creates additional challenges and risks.
- The uncertainties in the mass and other physical properties of any given candidate target NEA create multiple challenges. Paramount among these is the likely need to design to the worst-case of the potential range of insufficiently constrained properties (such as mass or size).
- Although there are indications that capturing a small NEA may be feasible, there remain substantial uncertainties regarding mission design that must be addressed. Further studies should concentrate on the translational maneuvers and mechanisms needed to capture any small free-flying NEA. These studies should include modeling of flexible structure dynamics and shearing inside the capture mechanism since the target could be monolithic, loosely bound, or a rubble pile.
- Additional trade studies are required to evaluate the mission concepts of capturing an entire small NEA versus collecting a small portion of a larger NEA. The latter option may be particularly difficult to design for without some a priori knowledge of the target structure.

Detailed Findings: ARRM Programmatics

- The feed-forward of ARRM to future human space exploration, including Mars, is unclear, and there has been insufficient study of potential alternatives that could achieve similar goals.
- Key aspects of ARRM remain undefined, resulting in lack of clear requirements and success criteria and the potential for high cost risk.
  - E.g., there is confusion as to whether the return of any asteroid sample to lunar orbit is a requirement.
- The ARRM schedule is too aggressive when coupled with technology development, mission complexity, multi-center implementation and funding uncertainties.
- The NASA-provided target cost (~$1B) is not substantiated.
  - Mission formulation studies and full-cost assessment are required.
  - NASA should consider competing ARRM to ensure sufficient technical scrutiny and peer review.
- Identification of ARRM as a “technology demonstration” is inconsistent with its high cost
- ARRM implementation planning/studies have not yet engaged international partners.
  - The compressed schedule may limit options for international participation.

Recommendations

- Establish clear ARRM requirements and success criteria that demonstrate how the mission contributes to future human space exploration.
- Establish a realistic and achievable schedule based on assessment of technical and programmatic requirements.
- Provide a realistic, independently assessed cost cap that fully accounts for all mission-related costs.
- Utilize the established processes of competition and peer review to define and assess the ARRM mission, to verify its feasibility within the established cost cap, and to determine and maximize the probability of mission success.
- Determine resources needed to provide upgrades to key ground-based observatories to improve detection rate and follow-up characterization capabilities.
- Improve remote characterization follow-up procedures with identified assets.
- Consider small robotic precursor missions to close characterization risks.
- Improve the engagement of the small body science community in mission planning

Next Steps

- Draft written report on Workshop website:

  http://targetneo.jhuapl.edu

- Draft available for comment thru ~Oct 14
  - Can send in comments through website or talk to any of the co-chairs
- Final report out by the end of October