Asteroid Redirect Robotic Mission (ARRM): Observation Campaign Study

Paul Chodas, NASA NEO Program Office

With assistance from: Lindley Johnson (HQ), Robert Jedicke and Eva Schunova (U. of Hawaii), Bob Gershman, Mike Hicks, Steve Chesley, Don Yeomans (JPL)
• Current population models suggest that there are a large number of good ARRM candidate targets, but current surveys are finding only 2 to 3 per year, and only 4 of the known candidates can be adequately characterized (2009 BD, 2011 MD, 2013 EC20, 2008 HU4).

• Discovery of good candidates is challenging, but the rate can be increased to at least 5 per year via near-term enhancements to current survey assets, as well as additional assets that can be online by 2015.

• Enhancing surveys to find more ARRM candidates also increases their capabilities for finding potentially hazardous asteroids in general.

• The discovery process alone is not sufficient to identify good candidates: physical characterization is also needed, particularly re size and mass.

• Radar is a key characterization asset for ARRM candidates.

• Rapid response is critical for physical characterization of newly discovered ARRM candidates. The process has been successfully exercised for a small candidate asteroid.
• 99% of Near-Earth Objects are asteroids (NEAs).
• Current number of known NEAs: ~10,000, discovered at a rate of ~1000 per year.
• Since 1998, NASA’s NEO Observation Program has led the international NEO discovery and characterization effort; this responsibility should continue in the search for smaller asteroids.
• 95% of 1-km and larger NEAs have been found; the completion percentage drops for smaller asteroids because the population increases exponentially as size decreases.
• Numbers for 10-m-class NEAs:
  - Estimated population: ~100,000,000
  - Number currently known: ~380
  - Estimated number that meet ARRM orbital criteria: ~15,000
  - Number currently known: 14
• US component to International Spaceguard Survey effort has provided 98% of new detections of NEOs since 1998.

• Began with NASA commitment to House Committee on Science in May, 1998 to find at least 90% of 1 km NEOs.
  – Averaged ~$4M/year Research funding 2002-2010

• NASA Authorization Act of 2005 provided additional direction:
  “...plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near-Earth object catalogue within 15 years [by 2020].

• Current Program Objective: Discover ≥ 90% of NEOs larger than 140 meters in size as soon as possible.
  – Starting with FY2012, has $20.5M/year
Currently, most Near-Earth Asteroid discoveries are made by: Catalina Sky Survey (60%), Pan-STARRS-1 (30%), and LINEAR (3%).

Enhancements and new surveys can come online in the next 2 years. Some will require additional funding.

These enhancements will increase capabilities to find hazardous asteroids as well as ARRM candidate targets.
Discovery & Characterization Processes

Discovery, Orbit Determination, Rough Size Estimation

**Discovery & Initial Astrometry**
- Minor Planet Center
- NEO Program Office

**Physical Characterization**
- **Astronomy, Photometry, Light Curves, Colors**
  - Orbit, area/mass ratio, size, rot. rate, spectral type
- **Visible & IR Spectroscopy, IR radiometry**
  - Spectral type, size, & mass, possibly composition
- **Radar**
  - Precise Orbit, size & rotation rate

Existing automated processes

Screening for Objects of Interest
**Characteristics of ARRM Target Candidates**

\( V_{\infty} \) is the velocity of the asteroid relative to the Earth during an encounter, with the acceleration due to the Earth’s gravity removed.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Reference Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbital</strong></td>
<td></td>
</tr>
<tr>
<td>Orbit: ( V_{\infty} ) relative to Earth</td>
<td>(&lt; 2 \text{ km/s desired; upper bound } \sim 2.6 \text{ km/s} )</td>
</tr>
<tr>
<td>Orbit: Natural approach to Earth</td>
<td>Orbit-to-orbit distance (&lt; \sim 3 \text{ million miles} )</td>
</tr>
<tr>
<td></td>
<td>Natural approach to Earth in early 2020s</td>
</tr>
<tr>
<td><strong>Physical</strong></td>
<td></td>
</tr>
<tr>
<td>Size and Aspect Ratio</td>
<td>Estimated mean size: 7 to 10 m</td>
</tr>
<tr>
<td></td>
<td>Upper limit on maximum dimension: \sim 14 m</td>
</tr>
<tr>
<td></td>
<td>Aspect ratio (&lt; 2:1 )</td>
</tr>
<tr>
<td>Mass</td>
<td>(&lt; 1,000 \text{ metric tons} )</td>
</tr>
<tr>
<td></td>
<td>(Upper bound decreases as ( V_{\infty} ) increases)</td>
</tr>
<tr>
<td>Spin Rate</td>
<td>(&lt; 2 \text{ rpm} )</td>
</tr>
<tr>
<td>Spectral Class</td>
<td>Known Type preferred, but not required</td>
</tr>
<tr>
<td></td>
<td>(C-type with hydrated minerals desired)</td>
</tr>
</tbody>
</table>
Current List of Potential ARRM Candidates

- 14 known asteroids meet the rough size and orbit criteria for ARRM.
- But, most were not physically characterized after discovery due to small size.
- These potential candidates are being discovered at a rate of **2-3 per year**.
- Enhancements to capabilities can increase this discovery rate.
- 4 candidates on this list can be at least partially characterized: 2009 BD, 2011 MD, 2013 EC20 and 2008 HU4.

### Table: Current List of Potential ARRM Candidates

<table>
<thead>
<tr>
<th>Name</th>
<th>Apparent Magnitude at First Detection</th>
<th>Estimated Size (m)</th>
<th>Earth Approach Date</th>
<th>Distance at Approach (AU)*</th>
<th>Maximum Returnable Mass (t)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 UN12</td>
<td>17.7</td>
<td>3 - 14</td>
<td>9/15/2020</td>
<td>0.043</td>
<td>490</td>
</tr>
<tr>
<td>2008 EA9</td>
<td>21.0</td>
<td>5 - 22</td>
<td>11/15/2020</td>
<td>0.073</td>
<td>130</td>
</tr>
<tr>
<td>2013 EC20</td>
<td>17.7</td>
<td>2 - 4</td>
<td>3/15/2021</td>
<td>0.067</td>
<td>120</td>
</tr>
<tr>
<td>2010 UE51</td>
<td>19.2</td>
<td>4 - 17</td>
<td>10/15/2022</td>
<td>0.023</td>
<td>130</td>
</tr>
<tr>
<td><strong>2009 BD</strong></td>
<td><strong>18.4</strong></td>
<td><strong>4 - 8</strong></td>
<td><strong>6/26/2023</strong></td>
<td>0.199</td>
<td><strong>590</strong></td>
</tr>
<tr>
<td>2011 MD</td>
<td>19.2</td>
<td>5 - 18</td>
<td>8/10/2024</td>
<td>0.150</td>
<td>690</td>
</tr>
<tr>
<td>2008 HU4</td>
<td>17.9</td>
<td>4 - 18</td>
<td>3/27/2026</td>
<td>0.149</td>
<td>1600</td>
</tr>
<tr>
<td><strong>2010 XU10</strong></td>
<td><strong>20.0</strong></td>
<td><strong>6 - 25</strong></td>
<td><strong>10/22/2021</strong></td>
<td><strong>0.167</strong></td>
<td><strong>TBD</strong></td>
</tr>
<tr>
<td><strong>2012 WR10</strong></td>
<td><strong>19.0</strong></td>
<td><strong>4 - 15</strong></td>
<td><strong>12/6/2021</strong></td>
<td><strong>0.292</strong></td>
<td><strong>TBD</strong></td>
</tr>
<tr>
<td><strong>2011 BQ50</strong></td>
<td><strong>22.8</strong></td>
<td><strong>4 - 17</strong></td>
<td><strong>11/4/2022</strong></td>
<td><strong>0.078</strong></td>
<td><strong>TBD</strong></td>
</tr>
<tr>
<td><strong>2011 PN1</strong></td>
<td><strong>22.0</strong></td>
<td><strong>6 - 24</strong></td>
<td><strong>6/30/2023</strong></td>
<td><strong>0.300</strong></td>
<td><strong>TBD</strong></td>
</tr>
<tr>
<td><strong>2005 QP87</strong></td>
<td><strong>18.2</strong></td>
<td><strong>5 - 22</strong></td>
<td><strong>3/1/2024</strong></td>
<td><strong>0.457</strong></td>
<td><strong>TBD</strong></td>
</tr>
<tr>
<td><strong>2010 AN61</strong></td>
<td><strong>19.4</strong></td>
<td><strong>7 - 30</strong></td>
<td><strong>6/10/2025</strong></td>
<td><strong>0.251</strong></td>
<td><strong>TBD</strong></td>
</tr>
<tr>
<td><strong>2013 GH66</strong></td>
<td><strong>20.3</strong></td>
<td><strong>5 - 18</strong></td>
<td><strong>4/15/2025</strong></td>
<td><strong>0.894</strong></td>
<td><strong>TBD</strong></td>
</tr>
</tbody>
</table>

*1 AU = 93,000,000 miles;  †Assumes Falcon Heavy launch vehicle and launch dates no earlier than 2017.
Primary Enhancements for ARRM Candidate Discovery

- **NEO Time on DARPA Space Surveillance Telescope**
  - Large 3.6m telescope, first light: Feb 2011, now in testing.
  - Eventual operations by AFSPC for DoD Space Situational Awareness.

- **Enhancing Pan-STARRS 1, Completing Pan-STARRS 2**
  - Increase NEO search time to 100% on PS1: Early 2014.
  - Complete PS2 (improved copy of PS1): Late 2014.
  - Simulations suggest the ARRM candidate discovery rate for PS2 alone at 100% will be ~5 per year.

- **Accelerated Completion of ATLAS**
  - Set of small telescopes with extremely wide fields of view covering the entire night sky every night, but not as deeply.
  - Final design selection soon. Completion: Early 2015.
  - Simulations suggest the ARRM candidate discovery rate for ATLAS will be ~10 per year.
## Options for Increasing the ARRM Candidate Discovery Rate

<table>
<thead>
<tr>
<th>Facility</th>
<th>$V_{\text{lim}}$</th>
<th>FOV (deg$^2$)</th>
<th>In Work or Potential Improvements</th>
<th>Ops Date</th>
<th>Notional ARRM discoveries per year$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current Surveys</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catalina Sky Survey:</td>
<td></td>
<td></td>
<td>Increase ML field of view 4x</td>
<td>Late 2013</td>
<td>2-3</td>
</tr>
<tr>
<td>Mt. Bigelow</td>
<td>19.5</td>
<td>8</td>
<td>Increase MB FOV 2.5x</td>
<td>Late 2014</td>
<td>1-2</td>
</tr>
<tr>
<td>Mt. Lemmon</td>
<td>21.5</td>
<td>1.2</td>
<td>Retune observation cadence</td>
<td>Mid 2014</td>
<td>3-5</td>
</tr>
<tr>
<td>Pan-STARRS 1</td>
<td>21.5</td>
<td>7</td>
<td>Increase NEO time to 50%</td>
<td>Late 2013</td>
<td>2-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increase NEO time to 100%</td>
<td>Early 2014</td>
<td>4-8</td>
</tr>
<tr>
<td><strong>Future Surveys</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DARPA SST</td>
<td>22+</td>
<td>6</td>
<td>Schedule some NEO time</td>
<td>Sep. 2013</td>
<td>2-5</td>
</tr>
<tr>
<td>Palomar Transient Facility (PTF)</td>
<td>21</td>
<td>7</td>
<td>Improve software to detect streaked objects</td>
<td>Late 2013</td>
<td>1-2</td>
</tr>
<tr>
<td>Pan-STARRS 2</td>
<td>22</td>
<td>7</td>
<td>Request 100% NEO time</td>
<td>Late 2014</td>
<td>5-10</td>
</tr>
<tr>
<td>ATLAS (North)</td>
<td>20</td>
<td>40</td>
<td>Entire night sky every night x2</td>
<td>Early 2015</td>
<td>8-16</td>
</tr>
</tbody>
</table>

$^*$Discoveries per year that meet ARRM’s rough size and orbit criteria for retrieval. $V_{\text{lim}} =$ limiting magnitude
N.B. Predictions for future discovery rates are based on extrapolated coverage and cadence.

**Discovery rates are not additive. There will be duplications of detections, particularly in the optimistic scenarios.**
Summary on Future Discovery Rate of ARRM Candidates

• The ARRM candidate discovery rate will almost certainly increase due to enhancements to existing surveys and new surveys coming online.

• Several asteroid survey enhancements are already in process and funded by the NEOO Program. Some could be accelerated with additional funding.

• A conservative projection, based on study of enhancements, is that the discovery rate will increase to at least 5 per year.

• Search for ARRM candidates will continue until final selection.

• With at least another 3-4 years to accumulate discoveries, at least 15 more candidates are expected.

• With rapid post-discovery characterization capabilities in place, there will be better opportunities to physically characterize future ARRM discoveries.

• Enhancing surveys to find more ARRM candidates also increases their capabilities for finding potentially hazardous asteroids in general.
Physical Characterization of ARRM Candidates

- **Radar** is essential for obtaining an accurate estimate of size and shape to within ~2 m, as well as rotation state.
- Ground-based and space-based IR measurements are important for estimating albedo and spectral class, and from these an approximate density can be inferred.
- **Light curves** are important to estimate shape and rotation state.
- **Long-arc high-precision astrometry** is important for determining the area-to-mass ratio.
- Mass is estimated from size and shape using an inferred or assumed density, and it should be constrained by the estimate of the area-to-mass ratio. Even so, mass may only be known to within a factor of 3 or 4.
- Final ARRM target selection may depend largely on how the estimated upper bound on the mass of each candidate compares with the return mass capability for that candidate.

Assumed albedo $\rho = 0.04$

Assumed albedo $\rho = 0.34$
Radar Observations of NEOs

- These are complementary capabilities.
- Currently, 70-80 NEOs are observed every year.
- A 10-m-class ARRM candidate must pass within ~5 lunar distances to be detected; ~80% of the 14 known candidates could have been detected.
- Radar observations can provide:
  - Size and shape to within ~2 meters.
  - High precision range/Doppler orbit data.
  - Spin rate, surface density and roughness.
Infrared Characterization of NEOs

**NASA InfraRed Telescope Facility (IRTF)**
- Dedicated Planetary Science Observatory
- Characterization of Comets and Asteroids
- Spectroscopy and Thermal Signatures
- On-call for Rapid Response on Discoveries

**Spitzer Infrared Space Telescope**
- Orbit about Sun, ~176 million km from Earth
- In extended Warm-phase mission
- Characterization of Comets and Asteroids
- Thermal Signatures, Albedo/Sizes of NEOs
- Longer time needed for scheduling
NEA Characterization Process

- **Observations**
  - Initial detection, astrometry, photometry
  - Apparent magnitude
  - Rough orbit
  - Absolute magnitude
  - Phase curves
  - Colors, Spectroscopy
  - Thermal infrared
  - Spectral type
  - Astrometry over months or years

- **Intermediate parameters**
  - Light curves
  - Additional astrometry
  - Radar
  - Albedo
  - Density
  - Area/Mass Ratio

- **Objectives**
  - Rough Approximation of
    - Size
  - Precise
    - Approximate
    - Rotation, Shape
      - Precise orbit

- **Additional astrometry**
  - Initial detection, astrometry, photometry
    - Mass
      - Density
  - Spectroscopy
    - Albedo
      - Mass
  - Thermal infrared
    - Approximate
      - Area/Mass Ratio

Asteroid Redirect Mission • Mission Formulation Review • For Public Release
• Discovered 7 March 2013 (during ARM study), by Catalina Sky Survey.
  – Initial size estimate: ~6m, Close approach 8 March at 0.5 lunar distance.
• Manually recognized as potential ARRM target (process now automated).
• Request follow-up astrometry ⇒ orbit update to enable IRTF observation.
• IRTF Interrupt: Spectra and thermal IR [Moskovitz & Binzel]:
  – L- or Xe-type, inferred albedo range of 0.1-0.4, density range of 2.0-3.0 g/cc
  – Diameter = 2.6 - 8.4 m, mass = 20 - 930 t
  – Spin rate ~0.5 rpm
• Arecibo radar @~3 lunar dist. [Borozovic]:
  – Diameter = 1.5 - 3 m ⇒ albedo > ~0.4
  – Constrains mass to < 50 t
  – Spin rate: 0.5 – 2 rpm
• Preliminary mission design indicates a feasible retrieval trajectory for 2021.
• **Rapid response** after discovery is essential while the asteroid is within range of characterization assets, since the asteroid will not likely be any closer for many years.

• Need rapid response for **radar** observation at Goldstone and/or Arecibo. The Goldstone interrupt response process especially needs to be streamlined.

• **Follow-up astrometry** from the observing community is essential for characterization.

• Request interrupt observations from **IRTF** and other large-aperture assets that can provide thermal IR data for faint objects. (This may require additional interagency agreements for target-of-opportunity observing time.)

• Obtain high precision astrometry, photometry and light curve measurements from geographically dispersed observatories (e.g. Palomar, Keck, European Southern Observatory in Chile).

• Solicit support from smaller telescopes, including amateurs, to provide quick follow-up astrometry and photometry.
## Currently Known Characteristics of Current Candidates

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Confidence</td>
<td>OCC &lt; 4</td>
<td>Excellent</td>
<td>Good</td>
<td>Recoverable</td>
<td>Recoverable</td>
<td>Recoverable</td>
<td>Good</td>
</tr>
<tr>
<td>Orbit: Vinfinity (km/s)</td>
<td>&lt; 2 (&lt; 2.6 req.)</td>
<td>0.7</td>
<td>0.9</td>
<td>2.6</td>
<td>0.5</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Orbit: Natural return year</td>
<td>Early 2020s (2020-26)</td>
<td>2023</td>
<td>2024</td>
<td>2020</td>
<td>2026</td>
<td>2020</td>
<td>2023</td>
</tr>
<tr>
<td>Spin Rate (rpm)</td>
<td>&lt; 2</td>
<td>&lt; 0.01 [3]</td>
<td>0.1 [3]</td>
<td>&lt; 2 [6]</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Spectral Class</td>
<td>Known (C preferred)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>L or Xe</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

NEO Characterization Enhancements

Radar (Goldstone and Arecibo)
• Increase time for NEO observations.
• Streamline Rapid Response capabilities.

NASA InfraRed Telescope Facility (IRTF)
• Increase On-call for Rapid Response.
• Improve Instrumentation for Spectroscopy and Thermal Signatures.

Reactivate NEOWISE
• ~3 year warm phase dedicated to NEO Search/Characterization data collection.
Simulations suggest there are thousands of suitable ARRM candidate targets; the challenge is to find them.

Candidates are currently being discovered at the rate of 2-3 per year.

With several survey enhancements in process, and new surveys coming online within the next 2 years, the ARRM candidate discovery rate should increase to at least 5 per year.

Discovery enhancements will add capability to find hazardous asteroids as well as ARRM candidate targets.

Rapid response after discovery is critical for physical characterization of ARRM candidates. The process has already been successfully exercised for a difficult-to-characterize candidate.

Goldstone and Arecibo radars are key characterization assets for ARRM candidates because they provide accurate estimates of size and rotation state.

Other major assets for characterization are available. Interagency agreements for target-of-opportunity observing time from important non-NASA facilities (eg. Subaru) can be negotiated.