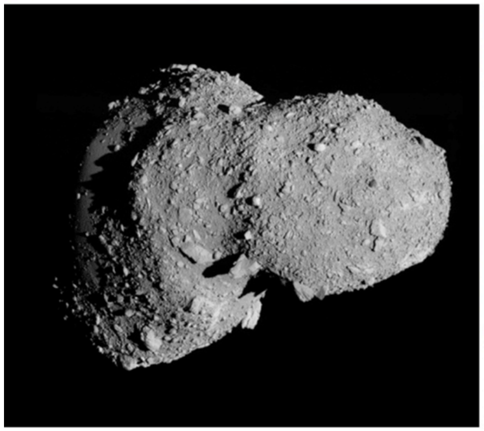
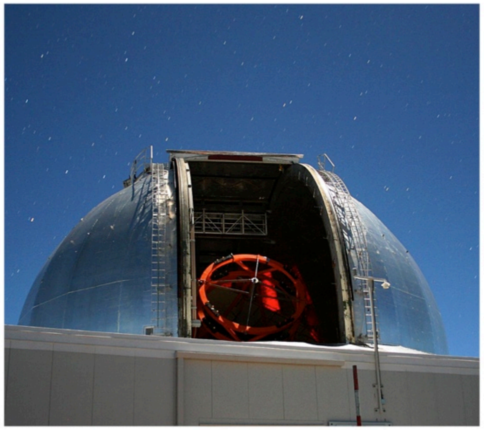
National Aeronautics and Space Administration

ARRM Capture System Trade Study Summary

Jasen Raboin





Outline

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  - Sizing Analysis
    - FEM (or hand calc) of Exoskeleton
    - Supporting Material Information
  - Mass Assessment
  - Launch Packaging
- **TALISMAN Concept**
  - Concept of Operations
    - Graphics of Deployment, De-Tumble, Retract, Restrain
  - Analysis of Salient Feature
    - Contact Dynamics of De-Tumble
    - Tool/End Effector Versatility
  - Sizing Analysis
    - FEM (or hand calc) of TALISMAN
    - Supporting Material Information
  - Mass Assessment
  - Launch Packaging
- **Conclusion/Recommendation**
  - Pro/Cons of Each Concept
  - Recommend Forward Work

Purpose & Team

Purpose

The purpose of the study is to provide an independent assessment of alternatives to the ARV capture system and recommendations on risk reduction investments leading up to the ARRM. This trade study focused on alternative capture systems to accomplish the mission, and alternatives to major sub-system functions within the reference concept.

Team Leadership (full team in backup)

Study Lead: Jasen Raboin (JSC)

Light Touch Leads: Judith Watson (LARC) & James Lewis (JSC)

TALISMAN Leads: John Dorsey (LARC) & Andre Sylvester (JSC)

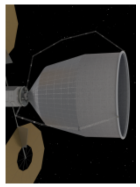
Center Leads: Scott Belbin (LARC), Stan Tieman (MSFC), Doug Willard (KSC)

Challenges of Asteroid Capture

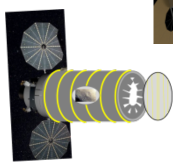
- Asteroid Redirect Retrieval Vehicle (ARRV) will operate in deep space for several years before encountering a ~1000t asteroid with an average diameter of 7-10m. The ARRV will use a sensor suite to characterize the asteroid and maneuver into a capture position by matching the asteroids translation and primary rotation.
  - The asteroid can have a 2:1 aspect ratio, resulting in a maximum dimension of ~14m
  - The mass (density) asteroid can vary from ground campaign predictions
  - Off-axis rotation and nutation movement will still be present during capture
  - Cohesion of asteroid material can vary (“rubble pile” vs. stony asteroid)
  - Surface properties will be unknown prior to launch
- An ideal capture system would be able to capture an asteroid with a range of multiple axis rotation, as well as low density and low cohesion material
- Slow spinners are more easily accommodated, but the ability to handle fast spinners expands the number of candidate asteroids
- Capture methods can not generate environments that create debris or excessive loads that may damage ARRV systems like the very large solar arrays required for electric propulsion.
- Launch vehicle and mission constraints require the capture system to be in the ~350kg range and fit within existing 5m shrouds.
- Building a capture system that can accommodate these varying design parameters is a challenge

Concepts Considered

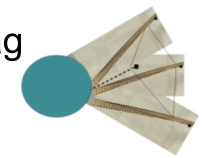
- 7 System concepts were reviewed
  - TALISMAN and Bag



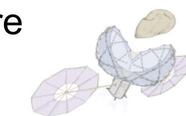
  - Space Port



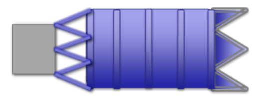
  - Deployable Booms with RCS and Bag



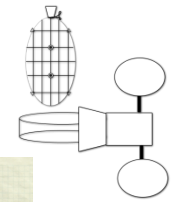
  - Hoberman Sphere



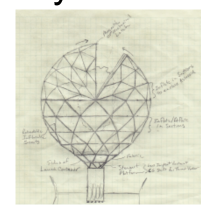
  - Peristaltic Concept



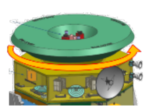
  - Remote Control Thruster



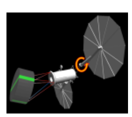
  - Light-Touch System



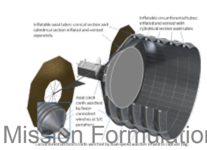
- 11 Sub-system concept were reviewed
  - Stiffeners
  - Ratchet Interface



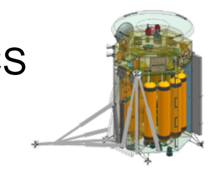
  - Pointing Solar Arrays



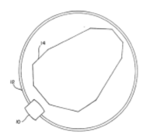
  - Internal Barrier



  - Deployable RCS

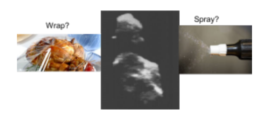


  - Lasso

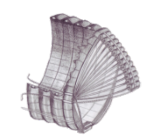


  - Electrostatic Gripper
  - De-Spinning w/ Tether

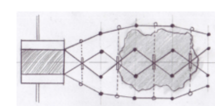
  - Coat Asteroid to Preserve Volatiles



  - Inflatable Dome Bag



  - Scissors and Cables



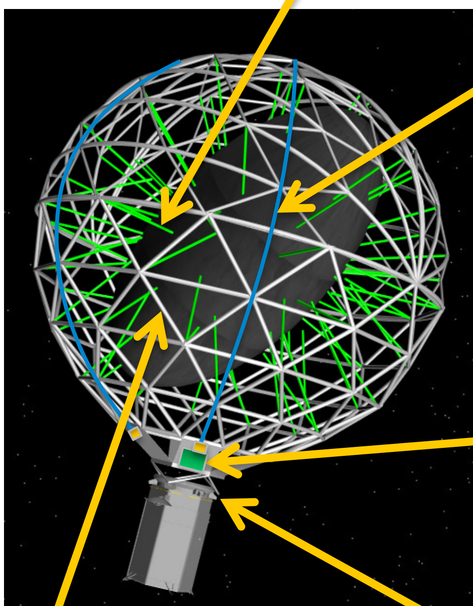
Down Select

- The team evaluated the different concepts against 8 figures of merit (see backup).
- Two main concepts were selected for further study w/ possible options within each concept
  - A deployable and retractable capture bag system that utilizes a **"Light Touch"** approach to de-tumble the asteroid over a period of time to minimize ARV array loads and simplify autonomous operations.
  - Tendon Actuated Lightweight In-Space Manipulators (**TALISMAN**) based system with end effectors, used in combination with capture bags, thruster packs, and other methods to bring added versatility to achieve mission objectives.

(It was determined later that there was not enough time allotted to study the potential options within each concept)

Light Touch - Concept of Operations

<u>Bristles</u> at each node apply light drag forces over time to de-tumble the asteroid, limiting loads on ARV arrays and allowing ARV to maintain attitude for power generation and communication during capture

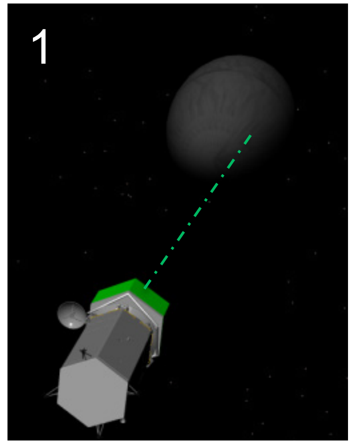


6 **<u>cable/winch</u>** systems attached to the platform base retract and restrain the asteroid

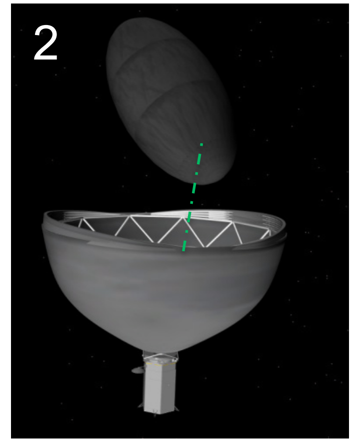
<u>Doors</u> in launch container/platform base provide EVA access and rigid work platform

<u>Stewart platform</u> gimbals the ARV to align SEP trust vector through asteroid CG

<u>Air beams</u> deploy to form a structurally efficient, pseudo geodesic exoskeleton with attached enclosure bag. The upper hemisphere is configured actuate closure during a staged inflation.

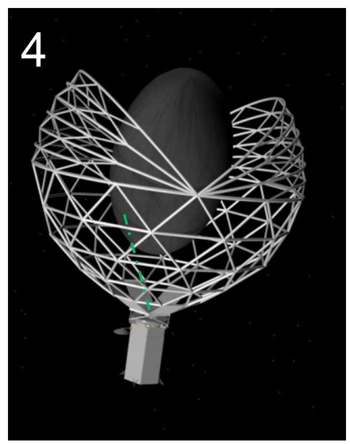


Rendezvous and Characterize

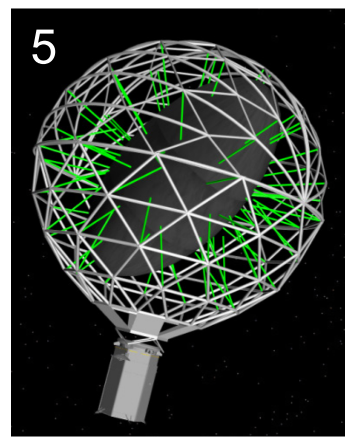


Deploy lower Hemisphere

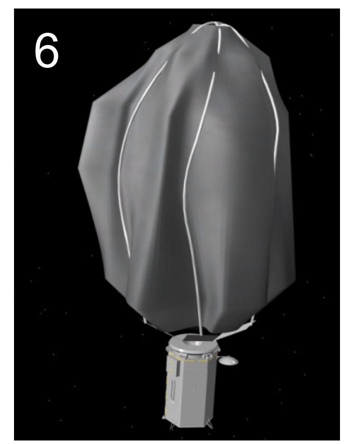
Center and match asteroid translation (no need to match spin rates)



Enclose



Deploy Bristles and De-Tumble



Retract, Restrain and Adjust CG

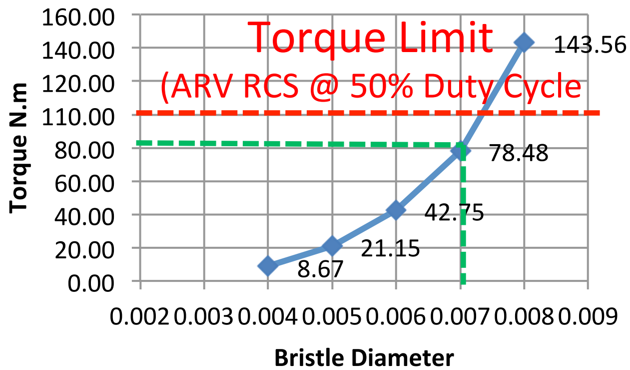
Light Touch – Analysis of Salient Features

- Contact Dynamics of Light Touch De-Tumble

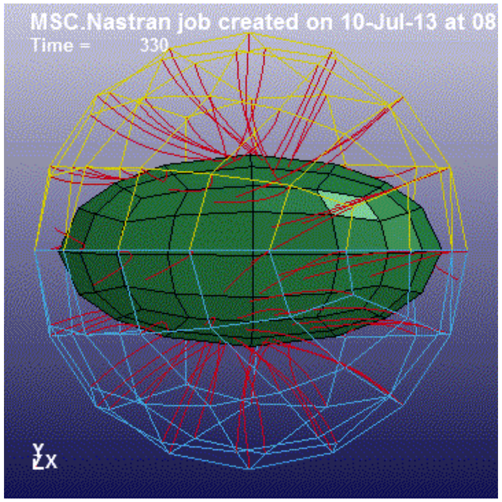
- **Case 1 Asteroid - Solid, axisymmetric ellipsoid**
  - Axes: 17.6 m, 8.8 m, 8.8 m (prolate)
  - Mass: 1,000,000 kg
  - Intial spin rate: 0.2 RPM
  - Nutation angle: 80.0 deg
  - Kinetic energy: 3,800 J
- **THIS CASE + 0.8 CoF DRIVES RCS MAX THRUST**
- **THIS CASE DRIVES SIZE OF ENCLOSURE BAG**

- **Case 2 Asteroid - Solid, axisymmetric ellipsoid**
  - Axes: 14.0 m, 14.0 m, 7.0 m (oblate)
  - Mass: 1,000,000 kg
  - Initial spin rate: 2.0 RPM
  - Nutation angle: 0.1 rad
  - Kinetic energy: 425,000 J
- **THIS CASE + 0.2 CoF DRIVES MAX DE-TUMBLE TIME**

Case 1 Torque

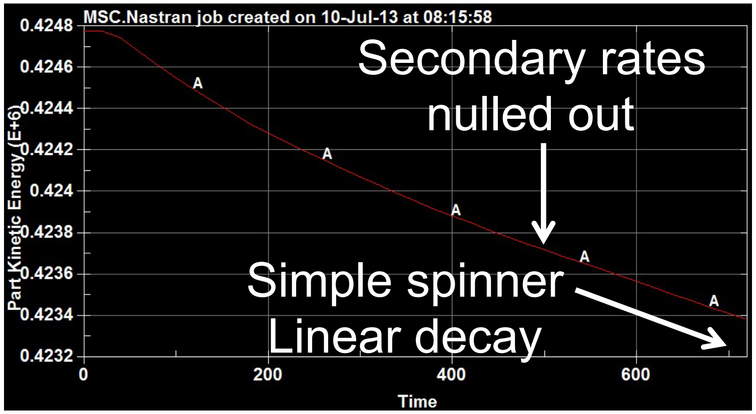


Results from Case 1 with high CoF (0.8) show that using a bristle with stiffness equivalent to a 7m long, 7mm dia Al rod, the max torque required to maintain attitude during de-tumble is **78 Nm**. Time to de-tumble is **42 min**.



LS Dyna contact dynamics model simulates ~100 bristles providing a light drag force on irregular surface asteroid

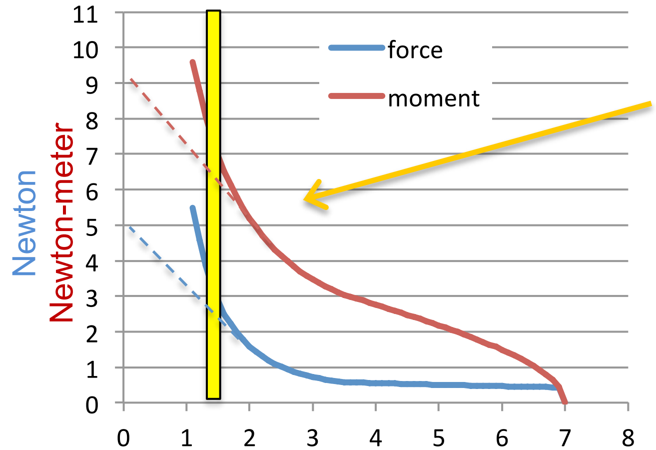
Case 2 Kinetic Energy



Results from Case 2 with low CoF (0.2) using the same bristle properties show that the time required to de-tumble the asteroid is **68 hrs**, with a max torque of **47 Nm**.

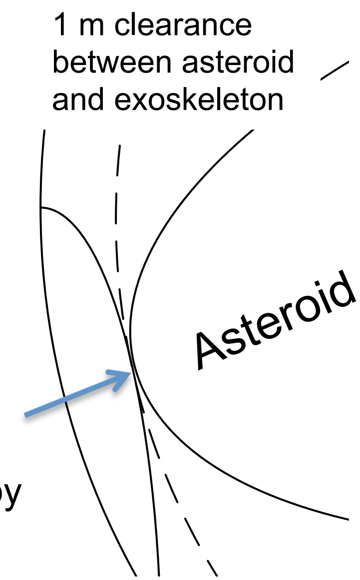
Light Touch – Sizing Analysis

- Bristle reaction force analysis



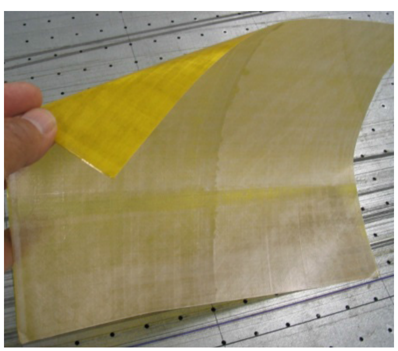
Reaction loads derived from Case 1 + 0.8 CoF model show max reaction force of ~4N & moment of ~8Nm at bristle attach location, well within the capability of envisioned exoskeleton structure.

Bristle simulated as a 7m long, 7mm dia Al rod
Max force imposed on asteroid by a single bristle = ~4N = ~0.8 lbf

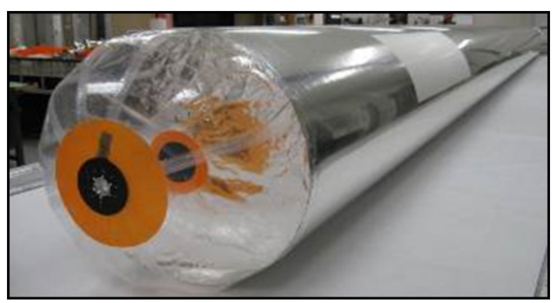


- Supporting Material Information

- Kapton/Mylar/Urethane coatings and air barriers
- Kevlar/Vectran/Dyneema fiber reinforcements



- Heritage space rated air beam designs exist that can be leveraged



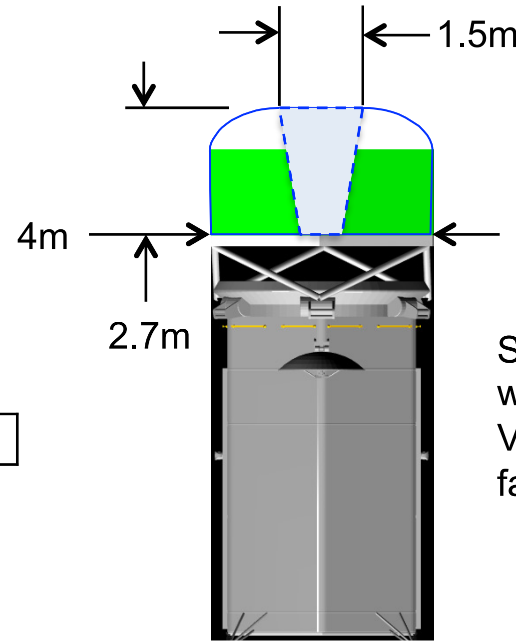
- Industry designs exist to leverage structural configurations

Light Touch – Mass & Launch Packaging Assessment

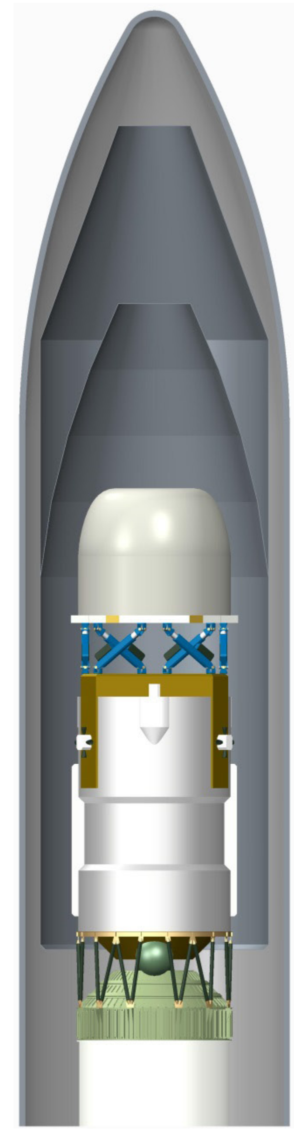
- System Mass

Gas System Mass	96.62 kg
Enclosure System Mass	214.19 kg
Structure Mass	34.00 kg
Attachments and Cabling	10.00 kg
Stewart Platform	100 kg
CBE	**454.81 kg**
Contingency Percentage	0%
Contingency Mass	0.00 kg
CBE + Growth Contingency	**454.81 kg**
Mass Bogey per JPL Design	350.00 kg
Mass Margin	**-104.81 kg**

- Launch Packaging



System fits well within the Altas V med & long fairings

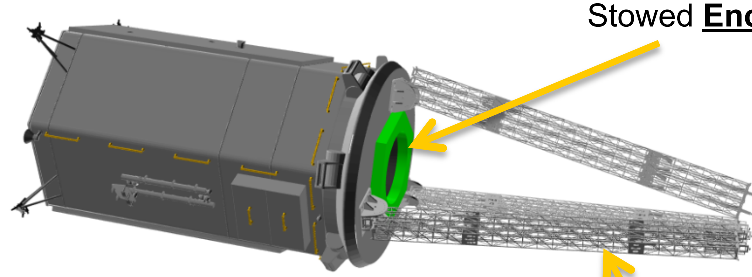


Sized for 20m Sphere
1256 m^2 of enclosure bag
1313 m of 0.2m dia air beams
(Qty 100) 7m long of 0.2m dia bristles
Packing Factor of 10 used for volume

Tendon Actuated Lightweight In-Space MANipulators (TALISMAN)

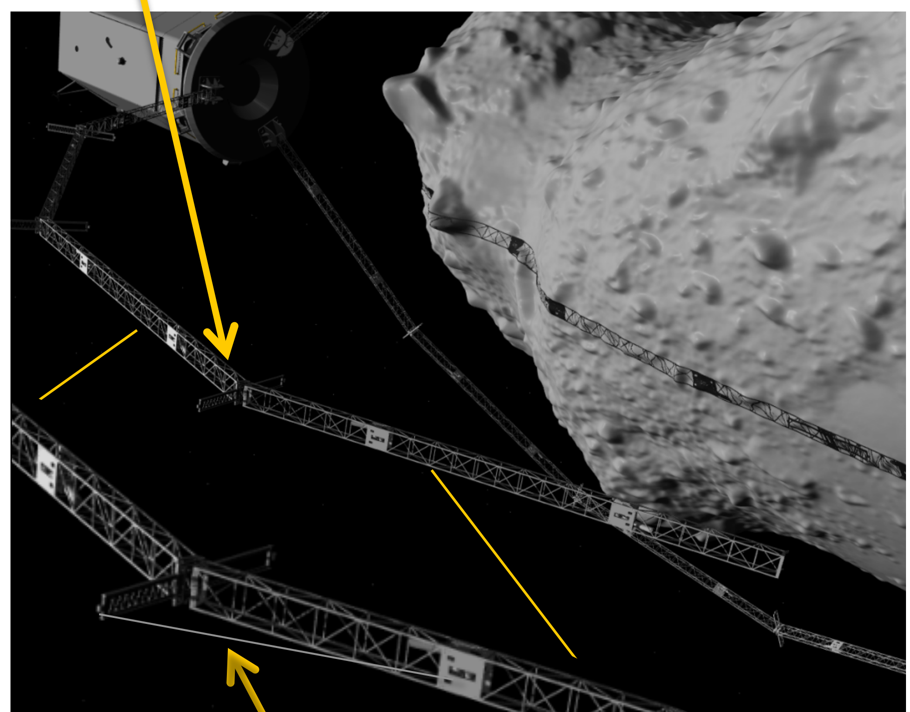
- Versatile, lightweight system that provides broad range of mission capture functionality
  - Much larger number of possible targets since large asteroid parent bodies are added to free-flying asteroids
  - Manipulator length gives spacecraft a long moment arm to maximize torque and minimize the propellant required to de-spin the asteroid
- Consists of two major subsystems
  - Set of 3 Tendon Actuated Lightweight In-Space Manipulators (TALISMAN) with End Effectors, and
  - Simple Lightweight Enclosure Bag

Stowed **Enclosure Bag**



Manipulators
Extended for grapple

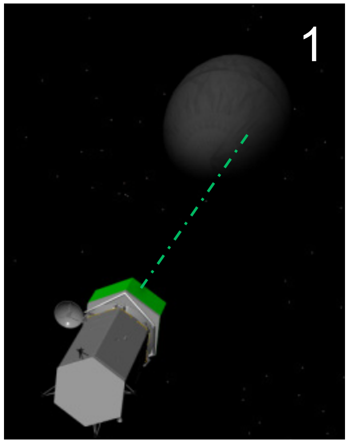
Three 4-Link **Manipulators** folded for Launch



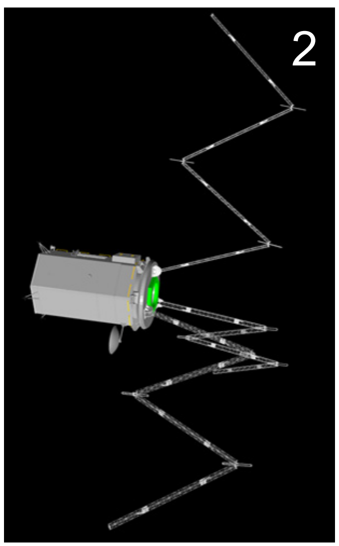
Tendon rotational joint detail

TALISMAN prototype lab where technology is currently being developed under the (STMD/GCD) Human Robotics Systems Project

TALISMAN – Concept of Operations



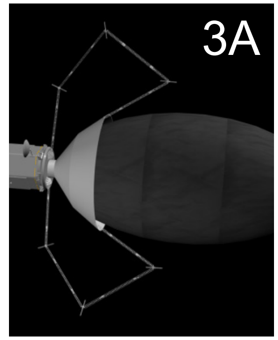
- Rendezvous
- Characterize



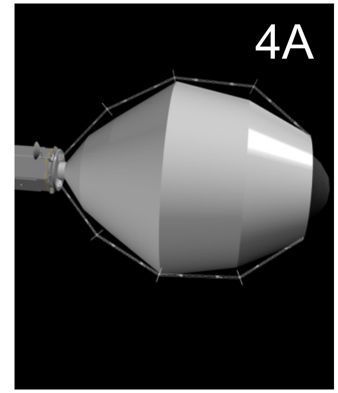
- Deploy Manipulators
- Select End Effector

Small, Slow Spinning Rubble Pile

- Match major spin axis rate
- Deploy Enclosure Bag
- Encapsulate Asteroid

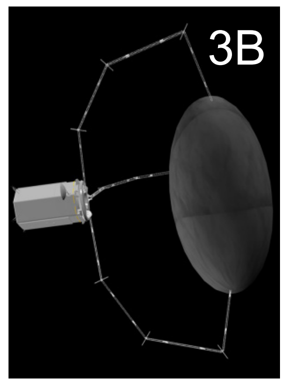


- Close Bag Opening
- Control ARV Loads by force feedback/ stroke control in arms
- De-tumble and Secure

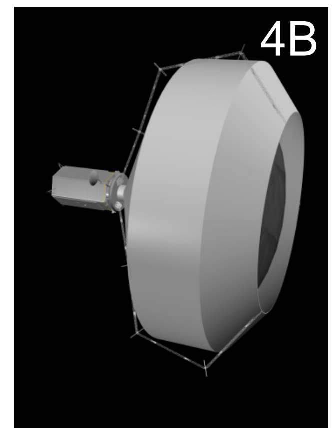


Small, Slow Spinning Solid Asteroid

- Match major spin axis rate
- Deploy Arms into position
- Instantaneously match minor spin rates
- Attach arms to asteroid

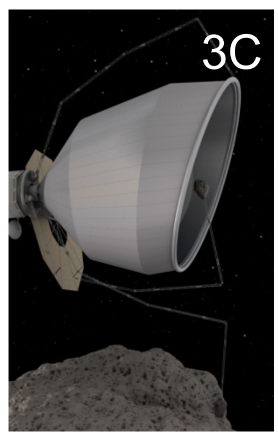


- Control ARV Loads by force feedback/ stroke control in arms
- De-tumble and Secure
- Encapsulate Asteroid in bag



Very Large, Slow Spinning Solid Asteroid

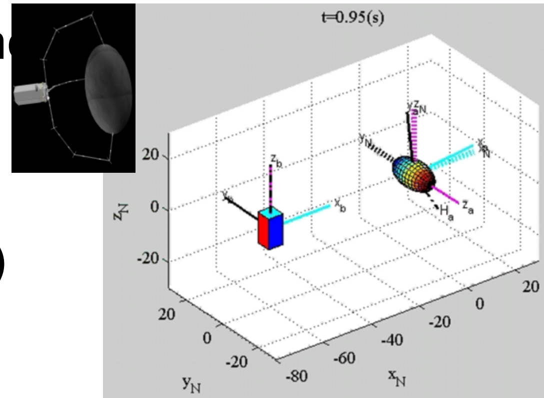
- Match major spin axis rate
- Deploy Enclosure Bag

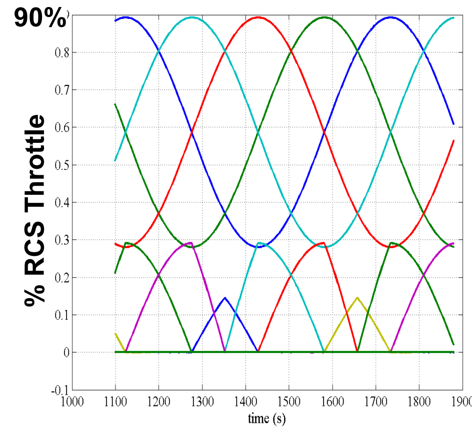


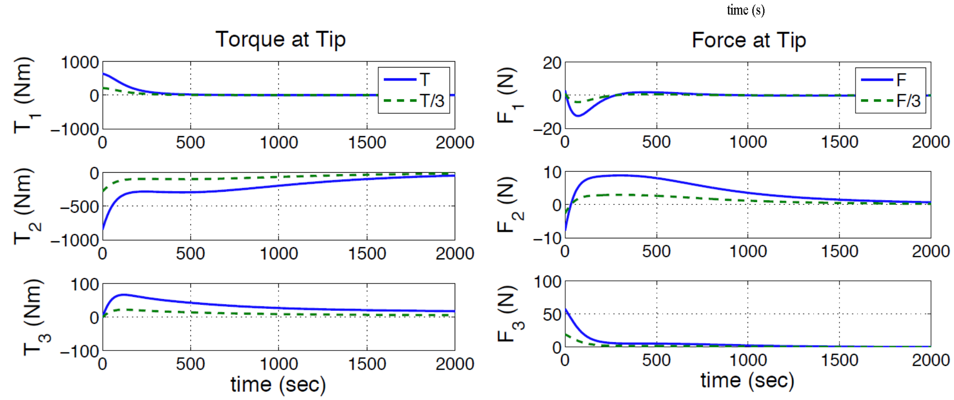
- Arm Tracks Surface Boulder
- Pluck Boulder from Surface
- Place in Enclosure Bag

TALISMAN - Analysis of Salient Features

- LaRC performed analysis to determine RCS forces and torques required to remove relative motion between the spacecraft and asteroid to allow capture (15.6 N and 22.2 N thrusters)
  - For asteroid Case 1, maneuver required 90% ARV RCS Thrust capability
  - Insufficient thruster authority to match rates for asteroid case 2
- LaRC performed analyses to determine de-tumble forces and moments on TALISMAN
  - Grapple with 3 arms with no relative motion between asteroid and spacecraft
  - De-tumble the asteroid/spacecraft system with RCS
- Assumptions
  - Rigid bodies analysis with single rigid manipulator
  - Peak loads occur at initial grapple/contact
  - Resultant loads shared equally between 3 TALISMAN



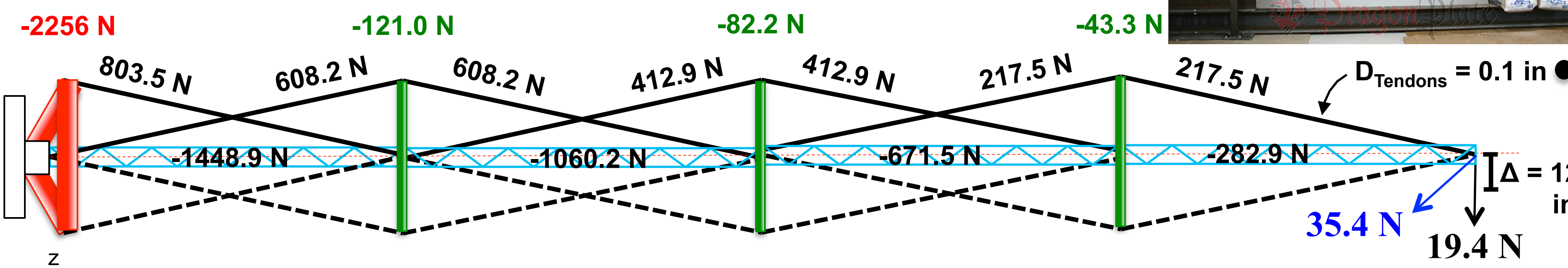


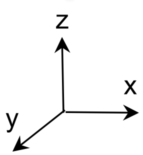


ANALYSIS RESULTS (Used For Sizing TALISMAN)	Asteroid Case 1
Maximum In-Plane Tip Force Resultant	19.4 N (4.4 lbf)
Maximum Out-of-plane Tip Force Resultant (Resolved from tip torque)	35.4 N (8.0 lbf)

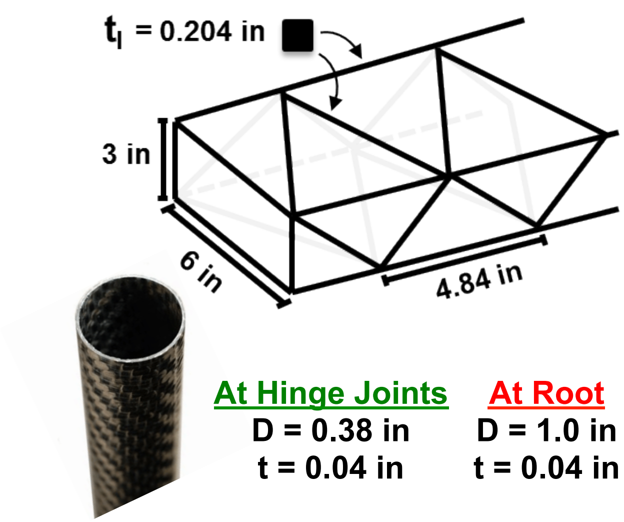
TALISMAN – Sizing Analysis for Asteroid Case 1

OVERVIEW
- L = 20m, 3x6 inch core truss. 4-links with 5 total degrees-of-freedom
- Composite truss / spreaders with high-stiffness polymer tendons
- Analysis tool allows rapid optimization of TALISMAN for wide-variety of missions





- *5 lb minimum pretension is actively maintained in dashed cables when tip load is applied*
- *Member loads shown are from in-plane applied load. Out-of-plane loads are added to maximum truss load for sizing*
- *Buckling drives truss and spreader sizing for this case, not strength (checks were performed using FS=2)*



Member	Material Properties			Case 1 19.4N I 35.4N I	Mid 200N I 200N L	High 383N I 468N I
	E (Msi)	P (lbs/in³)	a_max (Ksi)	Mass (Kg)		
Truss	10	0.06	80	11.14	27.00	40.9
Spreaders	10	0.06	80	0.41	0.88	1.09
Tendons	20	0.06	120	0.60	6.21	11.89
			TOTAL:	12.15	34.1	53.91

Non-optimized

TALISMAN - Master Equipment List and Packaging Assessment

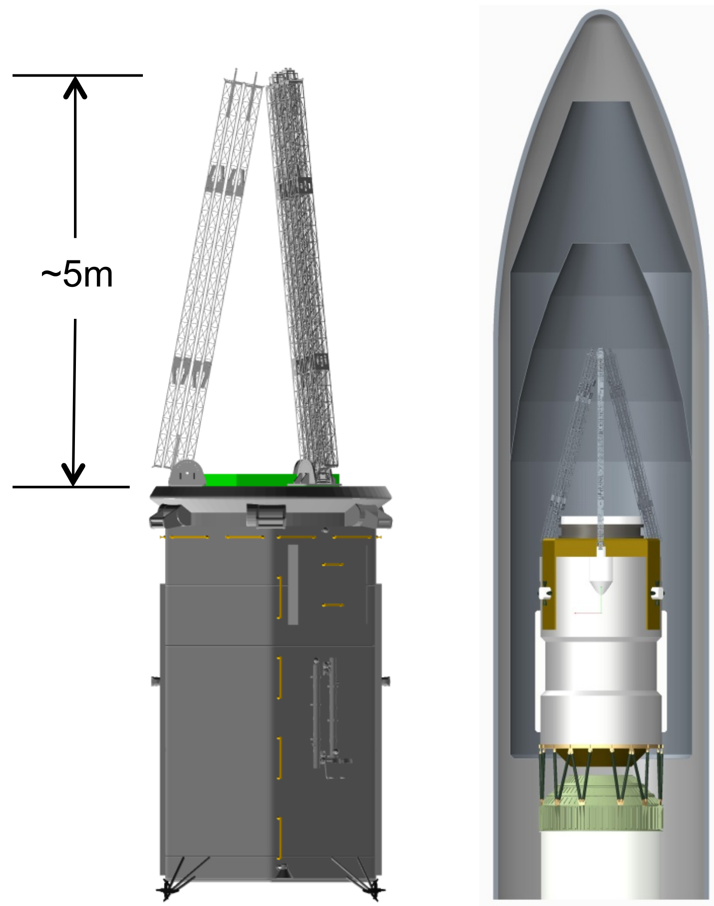
• System Mass

	Case 1	Mid	High	
Manipulator/Effector Sys Mass	129.69	309.09	511.85	kg
Enclosure System Mass	59.15	59.15	59.15	kg
Structure Mass	34.00	34.00	34.00	kg
Attachments and Cabling	10.00	10.00	10.00	kg
CBE	**232.84**	412.24	**615.00**	**kg**
Growth Contingency Percentage	0%	0%	0%	
Growth Contingency Mass	0.00	0.00	0.00	kg
CBE + Growth Con ngency	**232.84**	**412.24**	**615.00**	**kg**
Mass Bogey per JPL Design	350.00	350.00	350.00	kg
Mass Margin	**117.16**	**-62.24**	**-265.00**	**kg**

Non-optimized

Sized to manipulate a 17.6 x 8.8 x 8.8 m ellipsoid asteroid

• Launch Packaging



Atlas 5 Long & Medium Shroud

Conclusion - Pro/Cons of Each Concept

	Light Touch	TALISMAN
Pros	• Simple, controlled autonomous operations • No need to match spin rates • Maximize de-spin moment arm reduces prop usage • Maintain vehicle attitude during de-tumble (Power & Communication) • Passive load control during de-tumble • Potential to handle higher spin rate asteroids	• Manipulators can bring added mission versatility (inspection, sampling, drilling, prying, etc.) • Manipulators have the ability to conduct other mission objectives if asteroid is larger than predicted • Manipulators allow control of contact forces and SC Positioning during entire capture/de spin operations • Multiple TALISMAN provide mission and operational redundancy
Cons	• Higher weight (20m capture envelope + Stewart Platform) • Longer duration de-spin may increase prop usage • Large flexible structures will have dynamic, hard to predict zero-g deployment and reactration events	• Manipulators do not work well with a rubble piles or fast spinners • Coordinated mot ion of manipulators by autonomous control system will be a challenge • Require additional end-effectors (and mass) for inspection, sampling, drilling, prying, etc. operations

Recommendation – Forward Work

- For a mission targeting small (<20m) asteroids that could have relatively high spin rates and/or be a rubble pile, we recommend a continued investigation into "Light Touch" approach.
  - Complex contact dynamic modeling techniques for flexible structures
    - Complete exoskeleton/bristle flexible structure model
    - Rubble pile simulation

    (Analysis techniques can be applied to any concept)
  - Exoskeleton and Bristle development
    - Correlate coefficient of drag and stiffness characteristics
    - Demonstrate packaging, deployment, de-tumble and retraction
- For a mission targeting high solidity asteroids with low spin rates (<0.2rpm) that could be much larger than 20m, we recommend a continued investigation into the TALISMAN approach.
  - Optimization trade on prop required vs. manipulator capability to handle secondary spin rates
  - Study end effectors and control systems that minimize contact dynamics and increase ability to handle asteroids with higher spin rates

BACK UP SLIDES

Capture System Trade Study Team

Name	Center	Name	Center	Name	Center	Name	Center
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Harold Reimers	NASA JSC	Stan Tieman	NASA MFSC	Molly Selig	NASA JSC		

Figures of Merit

- **FOM 1: Versatility (with regard to baseline mission, asteroid characteristics)**
  - Multiple Asteroid Mission Capability (entire asteroid versus piece of asteroid)
  - Overall In-Situ Versatility
  - Adapt to Size, Shape and Spin of Asteroid (during development or in-situ)
  - Adapt to asteroid c.g. location and/or movement during capture or return
  - Ability to provide mobility on surface of asteroid
  - Crew Access/Facilitate EVAs (for science and/or system interrogation after return)
  - Ability to facilitate variety of tasks (drilling, grappling, anchoring, sample collection)
  - Ability to perform multiple capture attempts (re-settable)
- **FOM 2: Versatility (with regard to broader NASA goals)**
  - Scalability (including larger asteroids relevant to planetary protection)
  - Extensibility to Different Missions (In-Space Construction, Surface Operations, etc.)
  - Ability to facilitate variety of robotic tasks (drilling, sample collection)
  - Applicability to ISRU, commercial asteroid mining, etc.
- **FOM 3: Controllability**
  - Ability to exert capture, interaction, and de-spin loads (compliance, moment arm)
  - Ability to limit and control loads and motion imparted to spacecraft (including arrays)
  - Ability to secure asteroid to spacecraft during return
  - Contingency for release and/or recapture

Figures of Merit (cont)

- **FOM 4: Predictability, Verifiability, Reliability (Overall Design Simplicity/Complexity)**
  - Nondeterministic system aspects (soft-goods gathering, wrinkling, etc.)
  - Number and types of nonlinearities in system (soft goods load transfer, cables, etc.)
  - Number of Motors/Joints/Cables (total number, number of unique systems/components)
  - Deployment reliability and space-environment sensitivity
  - Feasibility of Relevant/Partial Ground Testing to (simulation inputs and verification)
  - Ability to Produce Accurate and Reliable Simulations (Including Monte Carlo Analysis)
  - Redundancy (ability to compensate if part of capture system fails, binds, etc.)
  - Number of steps in concept of operations to coordinate capture.
- **FOM 5: Technology Readiness (Heritage/Maturity)**
  - New technology requirements
  - System-level readiness & applicability of existing technology
  - Existence of legacy/similar/ground-based or in-space analogs
  - Readiness within desired/reasonable schedule
- **FOM 6: Mass**
  - Capture System Mass (all structure, motors, etc)
  - Mass sensitivity to changes in mission parameters
  - Efficiency of Load Path/Load Transfer
  - Need for Redundant Components/Systems

Figures of Merit (cont)

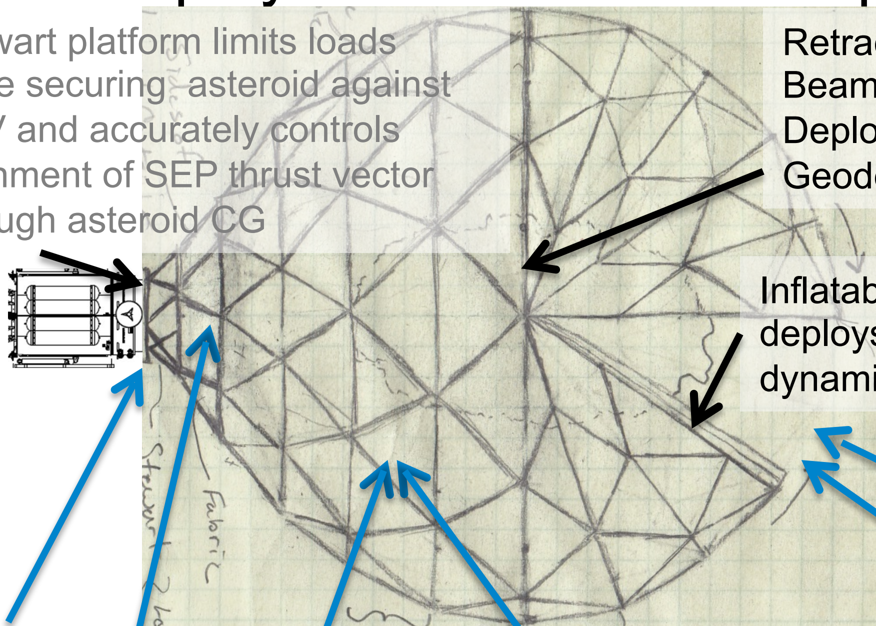
- **FOM 7: Launch Vehicle and Spacecraft Packaging**
  - System fits easily within LV shroud
  - System can be configured in various ways within LV shroud
  - System is easily integrated with SEP
- **FOM 8: Preservation of Asteroid**
  - Minimize changes to original asteroid surface
  - Minimize changes to original asteroid structure

Down Selected Concepts and Options

- Deployable/Retractable Capture Bag

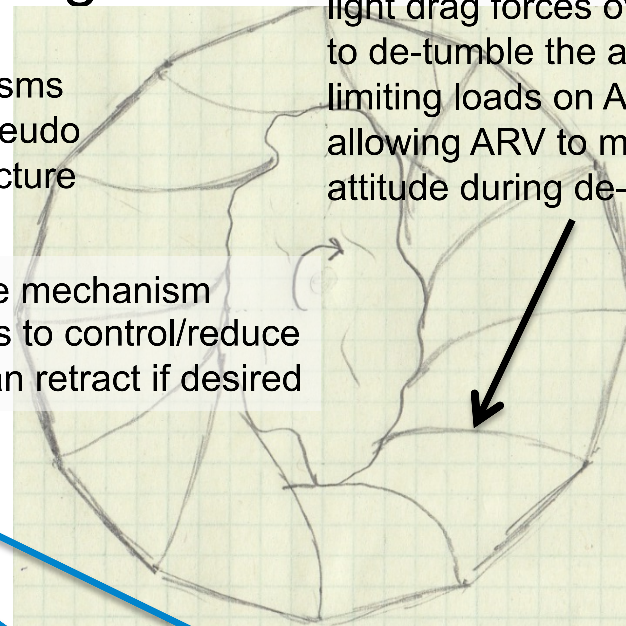
Stewart platform limits loads while securing asteroid against ARV and accurately controls alignment of SEP thrust vector through asteroid CG

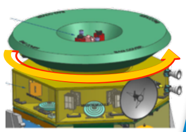
Retractable Air Beam Mechanisms Deployed in Pseudo Geodesic Structure



Inflatable capture mechanism deploys in stages to control/reduce dynamics and can retract if desired

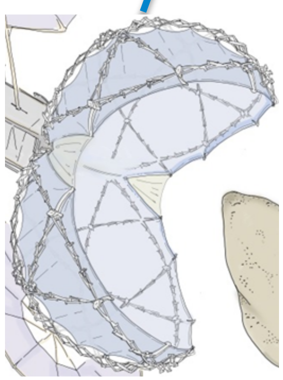
Bristles or Air Booms apply light drag forces over time to de-tumble the asteroid, limiting loads on ARV and allowing ARV to maintain attitude during de-tumble



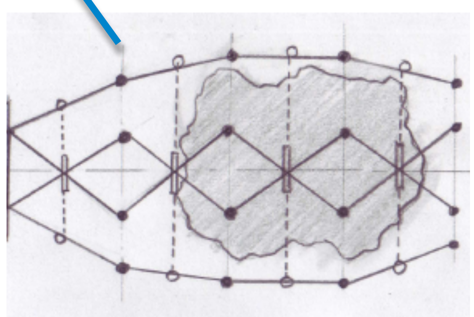


Ratchet Interface

Internal Barrier

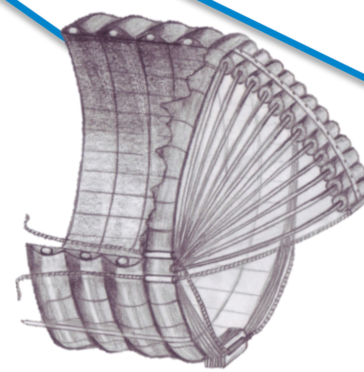


Hoberman Mechanism



Scissor Mechanisms

Optional Methods to Deploy Bag



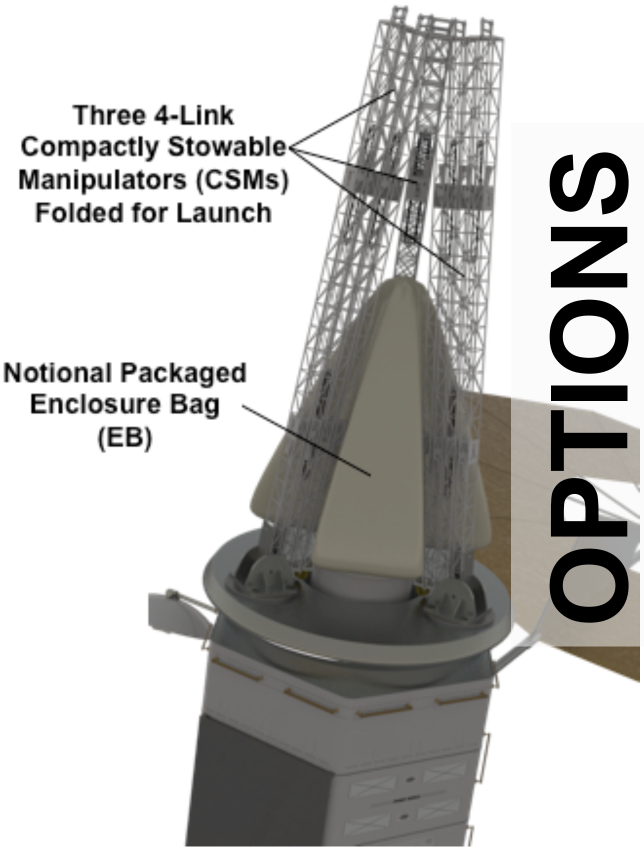
Bellowed Dome

Pneubotic Mechanisms

Optional Methods to Close Bag

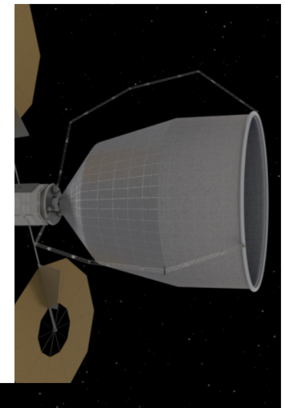
June 6th Down Selected Concepts and Options

- TALISMAN based system



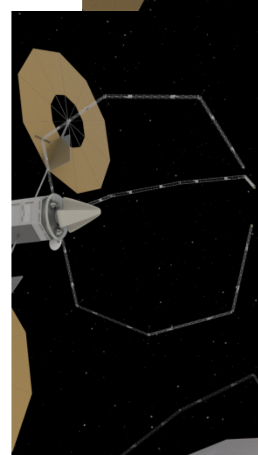
OPTIONS

Small, Slow Spinning Rubble Pile →



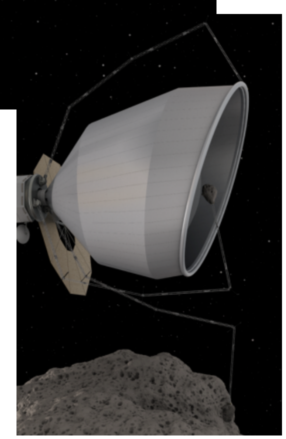
Light Touch De-Tumble
Bag and Secure

Small, Fast Spinning Solid Asteroid →



Remote RCS De-Tumble
Capture or Bag and Secure

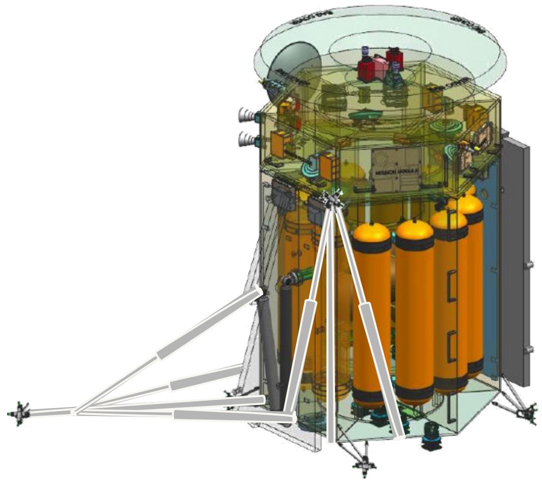
Very Large Asteroid →



Pluck from surface
Place in Bag and Secure

Other Options for Consideration

- Deployable RCS Boom for ARV
  - Increase moment arm, reduce propellant for de-tumble



- Pointing Solar Arrays
  - Multi axis rotary joint to allow power generation in off attitude conditions during de-tumble