Orbital Debris Removal and Proximity Operations

Input and Comments on the Robotics, Telerobotics, and Autonomous Systems Roadmap

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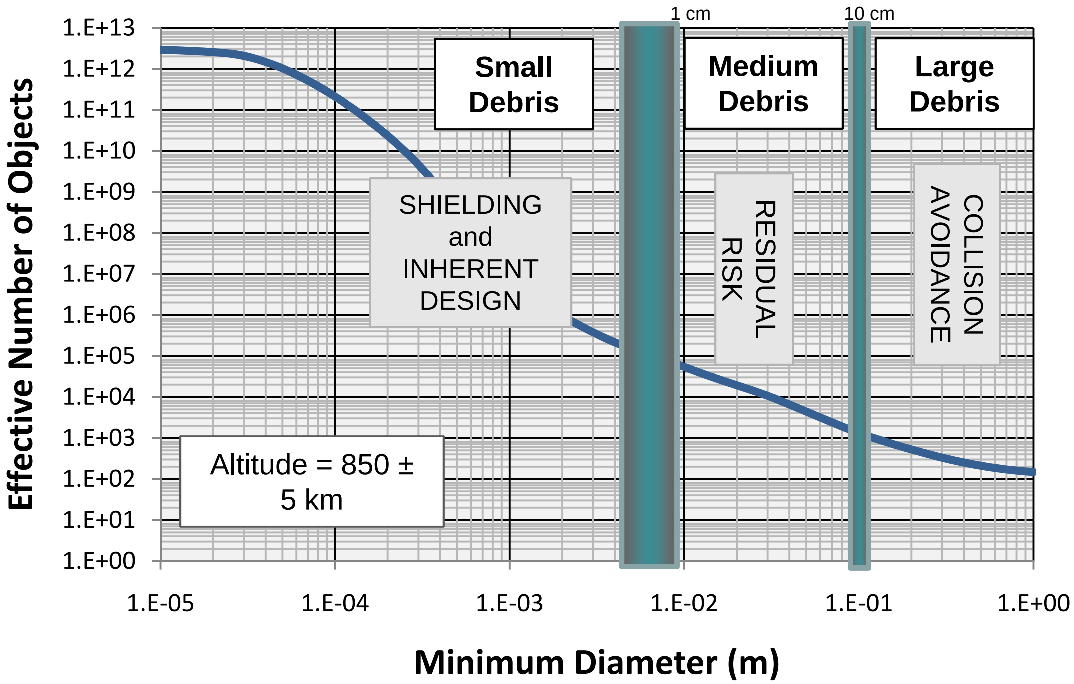
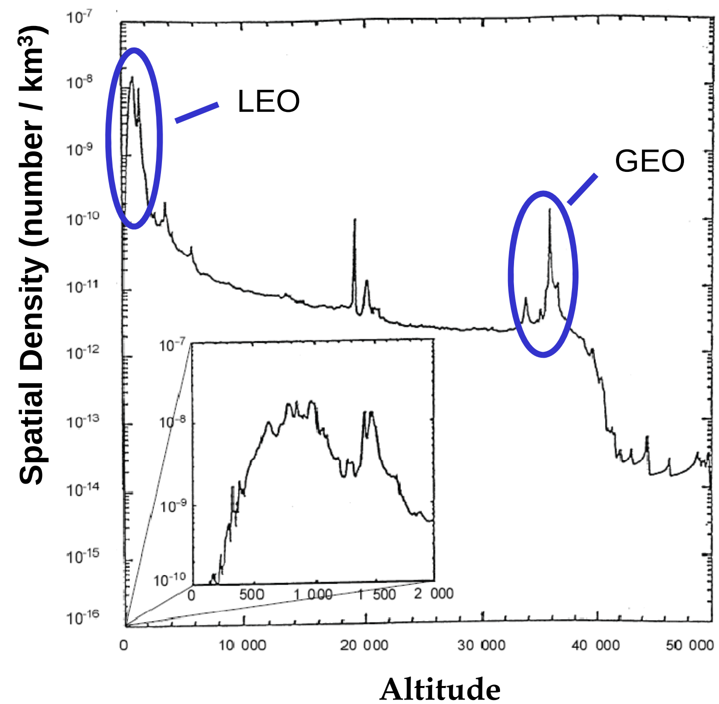
Expertise and Credentials

- Wade Pulliam
  - PhD Aerospace Engineering, Virginia Tech
  - DARPA/TTO PM
    - Various space programs PM
    - Catcher's Mitt study on orbital debris removal
- Jim Shoemaker
  - PhD Physics, AFIT
  - DARPA/TTO PM
    - Orbital Express, space surveillance telescope, Streak PM
- Marshal Kaplan
  - Ph.D. in Aeronautical and Astronautical Sciences, Stanford University
  - Senior Professional Staff, Space Systems Applications, Space Department, Applied Physics Lab

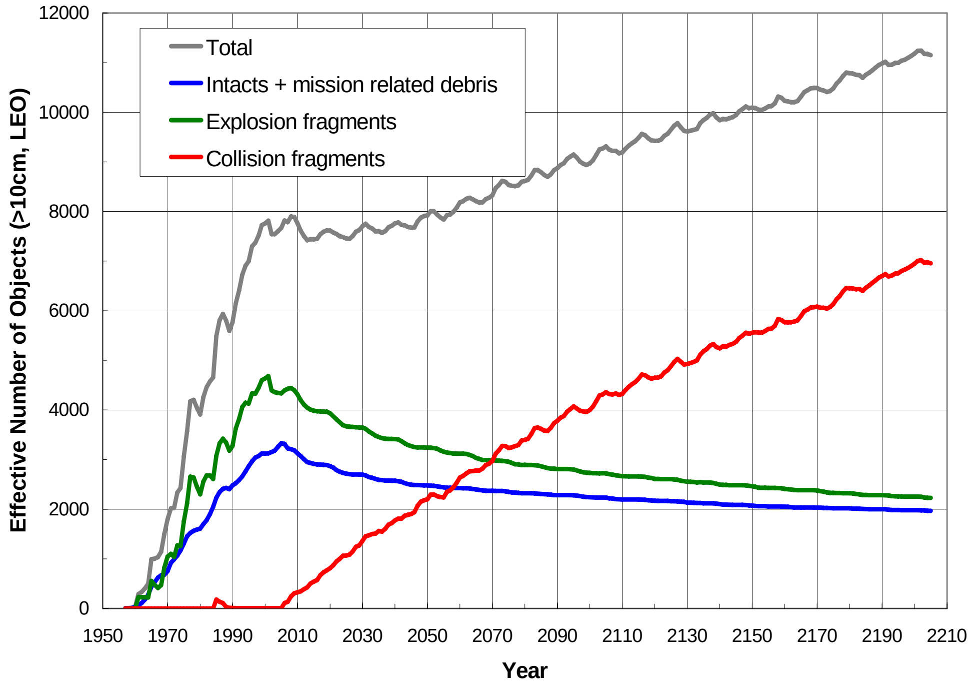
What Does Debris Look Like?



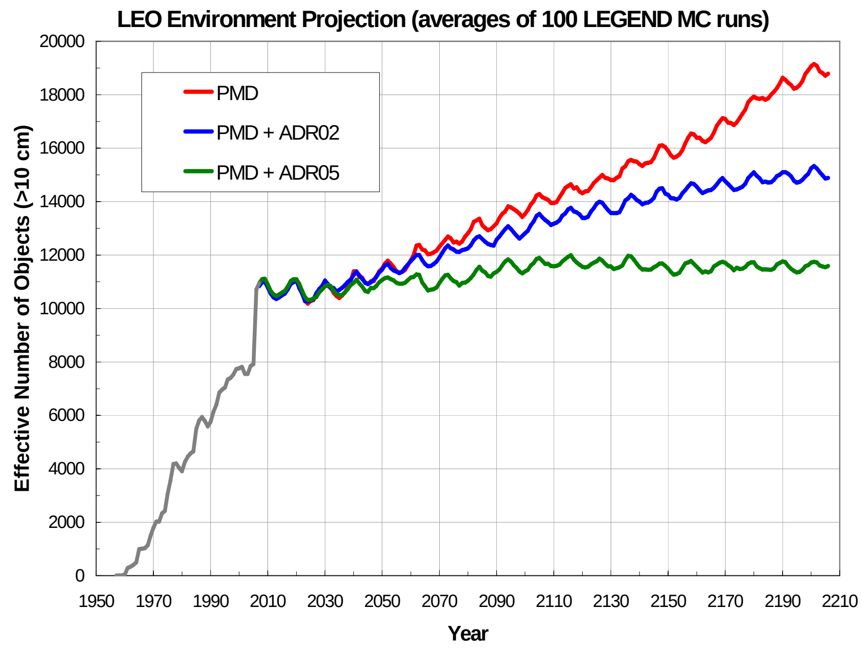


- The spatial density of debris is 100 X greater in LEO than GEO
- Vast majority of debris can be shielded against (< 5 mm); debris larger than this are potentially mission-terminating
- Large objects (> 10 cm) can be avoided, but this addresses only ~1% of the risk from potentially mission-terminating impacts.
- Large debris is only a small fraction of the population (15000-20000 objects)
- Object larger than 1 m are a small percentage (3000-5000 objects) but a vast majority of the mass
- The mass of the largest objects is the source of the future debris population growth, but the relativley small numbers is good in terms of a solution

Projections of the Future Debris Environment



NASA's Orbital Debris Program Office modeling of the future LEO (200-2000 km) debris environment for the extreme case of no future launches after 2005.



NASA's Orbital Debris Program Office modeling of the future LEO (200-2000 km) debris environment examining possible removal rates.

- The Inter-Agency Space Debris Coordination Committee (IADC) adopted (2002) a mitigation standard that calls for the removal of all launch items within 25 years of launch in an attempt to slow the increase in the debris population
- Note that simulation demonstrated that the debris population will continue to grow even without any additional launches – simulating the full and successful adoption of the IADC mitigation standard
- The conclusion is that mitigation standards will not be sufficient to stabilize the environment.
- According to NASA's Orbital Debris Program Office, removing 5 large objects per year from LEO is necessary stabilize the debris population in the long-term

Debris Removal Sequence

Precision Tracking, Rendezvous and Standoff

- **Find the RSO**
  - Determine the ephemeris uncertainty ellipsoid from CSSI and other sources. This ellipsoid can be reduced to a few hundred meters, assuming current tracking assets are focused on the object of interest in real-time.
  - Sensing the RSO as the tender approaches the ellipsoid and then executing relative GNC.
- **Rendezvous and Characterize**
  - Execute the rendezvous to a standoff position at a distance sufficient to avoid inadvertent contact or other adverse effects
  - Collect data in a tele-operated scenario in which visual and other images can be transmitted via telemetry to a ground controller.
  - Analyzing data and determining the best course of action
- **Dock or Grapple**
  - Maneuver into an appropriate position
  - Execute remediation sequence, grapple or attach a device
- **Stow the RSO or activate a removal device**

Sensing and GNC Functions vs Sensor Options

	Sensing and Discrimination				Guidance, Navigation and Control			
	Detection*	Tracking*	Prescreening*	Cueing*	Orbital transfer	Rendezvous	Inspection	Grappling
Ground radar	Initial acquisition	+ after handover	To optimize Δv maneuvers	+ fuse tracks	Minimize latency	Verify rendezvous	Not applicable	Not applicable
2-D imaging	In-space	Minimize covariance	To optimize Δv maneuvers	Verify radar	Fuse tracks	Verification of target	For outside linear nav	Backup contact verification
IMU	Not applicable	Supports triangulation	Not applicable	Attitude ref to fuse tracks	Attitude reference	Inertial position	Attitude update	Attitude maintainence
Star tracker	Alternate	Alternate	Not applicable	Attitude ref to fuse tracks	Correct IMU drift	Verify attitude	Not applicable	Not applicable
Passive stereo	FAR reduction	Sequential triangulation	Not applicable	Sequential triangulation	Not applicable	Proximity station keeping	Passive 3-D in sunlight	Good for HITL
Structured light	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Proximity station keeping	3-D in darkness	Facilitate contact
Lidar	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Effective given cue	3-D all conditions	Saturation in proximity
Gravity gradiometer	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Mass characterization	Not applicable

- **In situ sensors support detection, tracking, prescreening, station-keeping, orbital transfer, rendezvous, inspection, grappling, motion state estimation, and mass distribution estimation prior to terminal remediation tasks**
- **Principal functionality of each is cited in matrix entries, and relative utility is given by color (green = good to excellent, yellow = acceptable in most cases)**
- **“Not applicable” means sensors are not useful at standoff ranges**

Docking History Review

	Cooperative Target	Semi-Cooperative Target (stable, no capture aids)	Non-Cooperative Target (tumbling with no capture aids)
Autonomous Control	Yes (ETS-VII docking, Soyuz, Mir)	No	No
Ground Control	Yes (ETS-VII robot arm, Orbital Express)	No	No
Crew Control	Yes (Gemini, Apollo, ISS, LDEF, Solarmax, SPARTAN, Hubble)	No	No
Manual (EVA)	No (Unsuccessful with Solarmax)	Yes (Palapa/Westar, Leasat)	No

- Cooperative targets are routinely approached and docked with
- Non-cooperative (tumbling) target capture has never been attempted
  - No methods have even been demonstrated for capturing a non-cooperative target without damage
- Semi-cooperative targets can probably be captured given suitable grasping points, reliable approach algorithms and equipment, and a stable target vehicle

Technical Problem Areas Addressed -

Capture Techniques: Grappling

- **Key assumptions and caveats**
  - Large RSOs may not have convenient grapple attach points
  - Grappling devices must function on almost any shape object or surface
  - Viable approaches exist for grappling cooperative and non-cooperative (including tumbling) debris in close proximity
- **Operational issues**
  - Determination of suitable grappling/capture point(s)
    - Combination of hold points and determination of structural hard points at a distance
    - Machine vision/visual serveying for grapple point ID, tracking, capture is critical
  - Adequate joint and grapple torque/force control for rigidized and compliant grips
  - Attitude compensation for grapple arm motion + coupled debris-tender dynamics
  - Tele-operation time delay
  - Attachment of de-orbit kits
- **Other options to encapsulate or snare debris objects at stand-off distances:**
  - Encapsulating nets
  - Soft robotic mechanisms (tentacles)
  - Tethered harpoon or end-effectors
  - Tethered lassos

Technical Problem Areas Addressed -

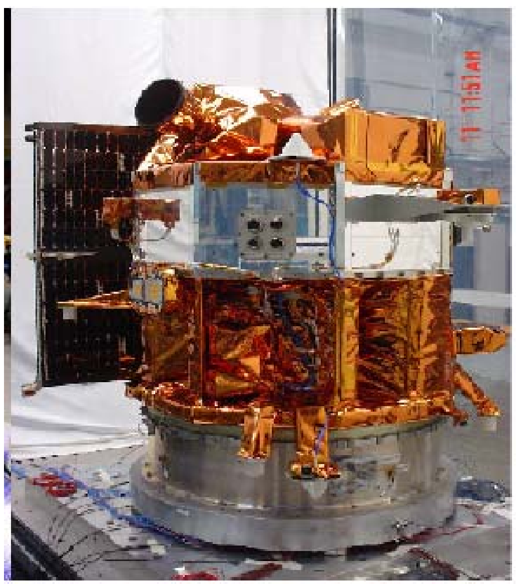
Capture Techniques: Assessment and Caveats

Figures of Merit → Potential implementations ↓	Mass per unit length/ area/volume	Maximum length/area /volume	Tensile strength or load capacity	Bending radius of curvature	Required actuator power	# of DOFs (control channels)	S/C - debris force/torque isolation
Robotic grappler*	High	Med	High	Small	High	6-8	Med to high
Inflatable longeron	Very low	Long	Low	Large	Low	1-2	High
Harpoon with tether	Low	Long	High	Small	Med[1]	1	High[2]
Articulated tether (lasso)	Med	Med	Med	Med	Med	3	Med to high
Encapsulating net	Low	Med	Med	Small	Low	N/A	High
Electrostatic/adhesive blanket	Very low	Med	Low	Small	Low	N/A	High

Caveats	
Robotic grappler	Optimal for close contact grappling requiring high torque or structural penetration in absence of grappling fixtures, mature technology. DOFs facilitate thrust aligment. * Representative: size: 65 x 49 x 186 cm^3 pre-launch; weight: 70-90 kg, power: 130 W
Inflatable longeron	Extremely lightweight and low cost, may be able to employ velcro for capture, may be suitable for drogue chute deployment, susceptible to leaks.
Harpoon with tether	1. High impulse-power, low average power, 2. Although force/torque isolation is good lack of contol/stability of angular DOFs is problematic, may be suitable for tractor thruster.
Articulated tether (lasso)	Controls angular DOFs using multiple radial actuators, has anti-torque advantages over simple cable tethers.
Encapsulating net	Low mass, low cost, doesn't control angular debris DOFs, but may be suitable for irregular shaped debris or appendages.
Electrostatic/adhesive blanket	Very light weight, may be suitable for initial contact and precursor attachment.

Orbital Express Demonstrated

Astro Servicer
(picture credit Boeing)



NextSat Servicer
(picture credit Ball)

- Monopropellant (hydrazine) fuel transfer
  - Pump and pressure driven
- Orbital replacement units transfer via robotic arm (simple end effector)
  - Battery and processor ORUs
- Capture and soft docking
- Multiple rendezvous and dockings
- Comparison of the utility of a variety of sensors
  - Optical and IR cameras
  - Laser ranger
- Autonomous POSE determination
  - Target based (Advanced Video Guidance System)
  - Image based pattern matching
- Basic autonomous anomaly handling (rendezvous abort)

Orbital Express - 6-month mission life demonstration for included technologies

Areas For Future Work for Satellite Servicing

- Improved fuel transfer
  - Oxidizers and other corrosive fluids
  - More reliable fueling coupling mechanisms
- More sophisticated vision recognition
  - Create a model on the fly instead of relying on a preexisting one
- Active and passive sensor fusion
- Vehicle with multiple arms and interchangeable end effectors
- Grappling non-cooperative, non passively stable objects
  - Attitude and Control System to match target object 3 axis rates
  - Development of multi-axis robot arms, including autonomous control and feature recognition; improve ability to capture targets with limited grasping provisions
- Attachment of orbital replacement units (ORU) to external satellite surfaces
  - ORU interface design improvements would help
- Robust autonomous anomaly handling
  - Identifying and correcting anomalies on the fly
- Human / robotics work collaboration

Most of this future work is already captured in the roadmap
RED items could provide revolutionary advances for the NASA mission – especially those beyond Earth orbit

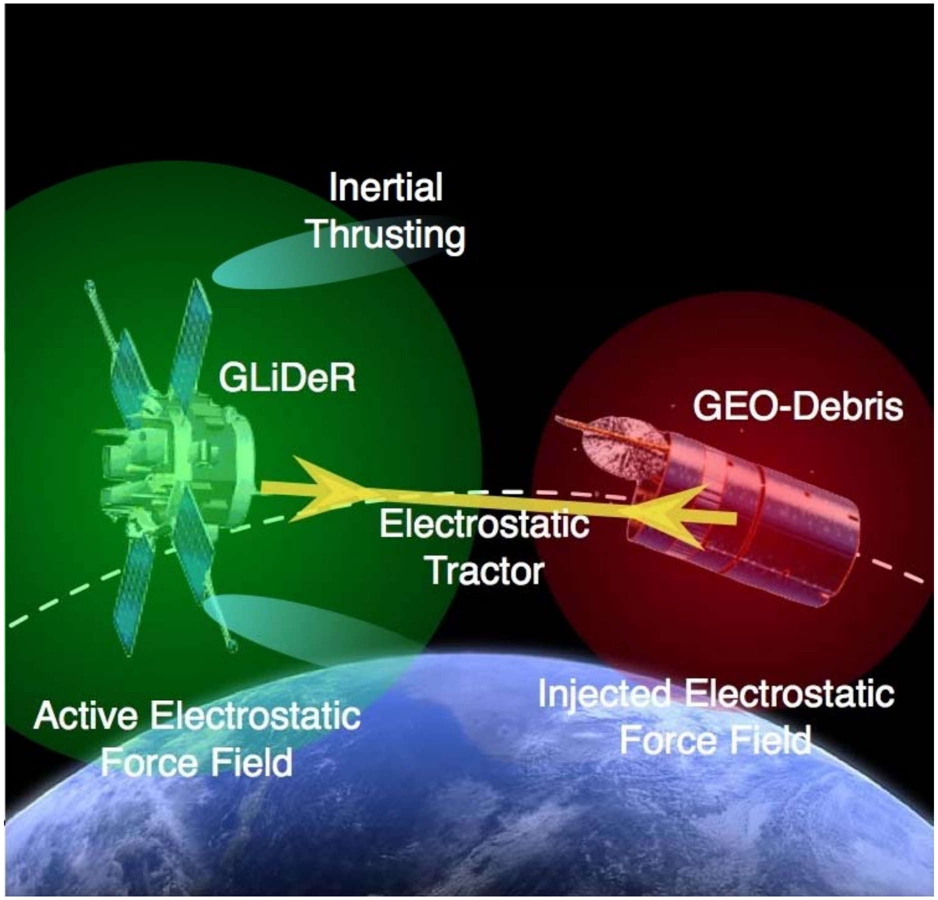
Technology Inputs to the Roadmap

- Passive/Active sensor fusion has the promise of getting the best of each (especially for rendezvous and inspection), although SWAP and cost may be an issue
  - Sensor fusion, due to large investments made my the ISR community, may be closer than imagined and could be adapted to the prox ops mission with a small investment
- Autonomous anomaly handling will speed operations in Earth orbit, but is required for prox ops in inter-planetary space
  - Alternatively, improved man/machine work collaboration is the right risk approach to LEO ops and maybe GEO, but unworkable farther out
- Grappling technologies appear to concentrate on grabbing man-made, intact objects. Grappling other objects is a gap not covered
  - This could handle some of the top targets for debris removal
  - What about true debris?
  - What about asteroids and other natural objects?
- Non-contact despinning and tugging may be an attractive option for many missions. This is especially true for those missions where the strength of the target object is unknown or whose tumbling is too complex or fast for prox ops
  - Electrostatic manipulation could be a game changer for such missions

Possible Game-Changing Approach Touchless Debris Moving

Geosynchronous Large Debris Reorbiter (GLiDeR)

- No physical contact required with the debris
- Reduced risk of collision by avoiding docking, and permitting debris to tumble
- Gently tug the entire debris object
- Simplified relative navigation with reduced relative motion sensing requirements
- Multi-year missions feasible moving 10-15 objects over lifetime, very economical per ton of debris moved
- Multi-ton debris can be reorbited in 3-4 months using 10’s of kilo-Volts



Touchless reorbiting is being developed via a joint effort of the Wacari Group and the University of Colorado.

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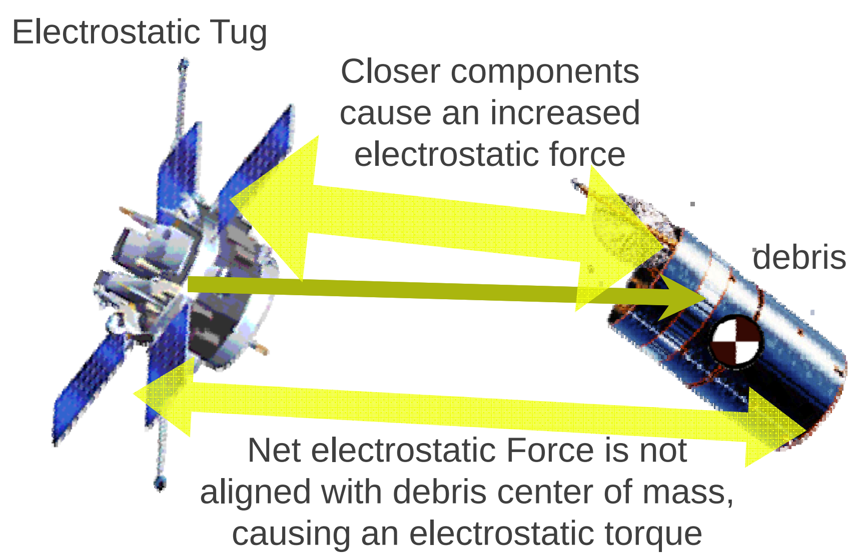
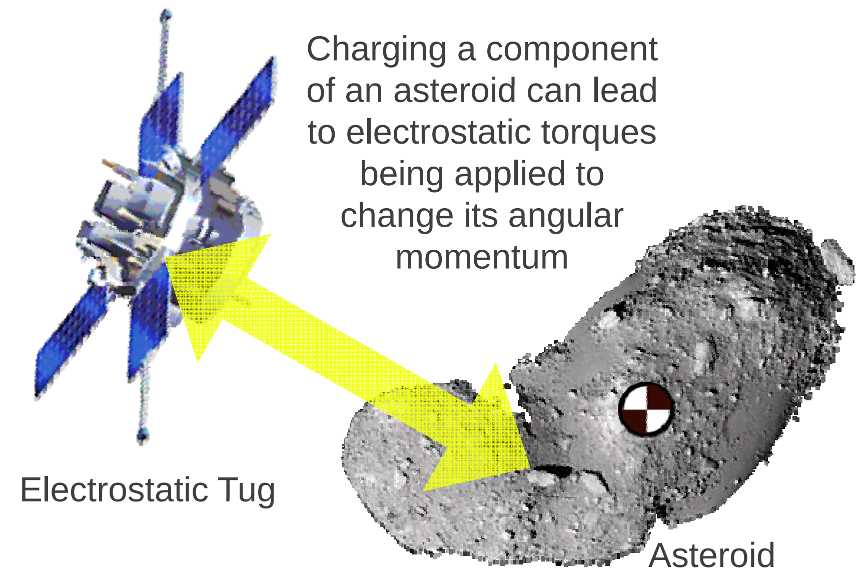
Electrostatic Torques to Despin





- Electrostatic torque can be used to slow down the existing spin rate using long-term station keeping without docking onto the object
- The efficiency of this process depends strongly on the three-dimensional shape of the spinning object, as well as the feasible charging levels and separation distances.

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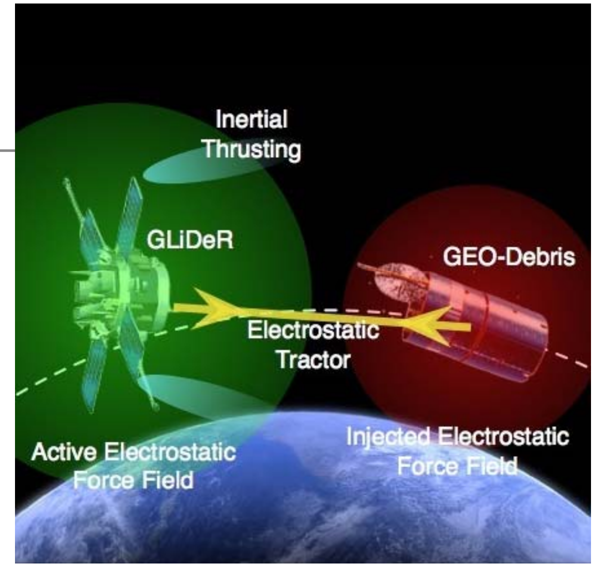
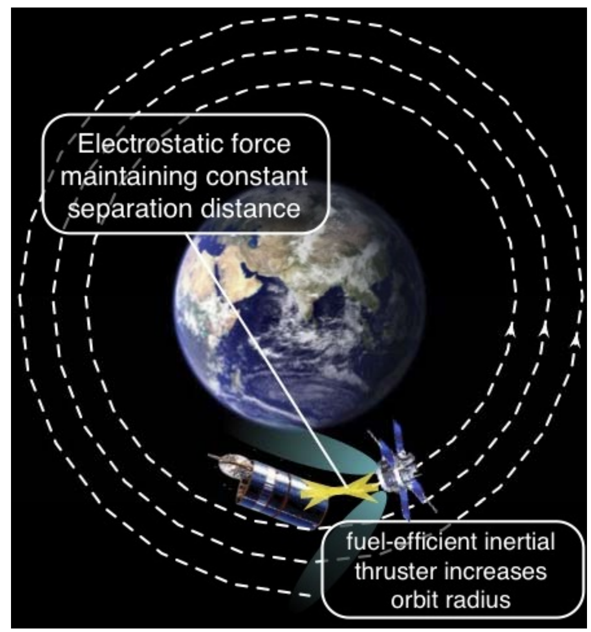
Technical Challenges

Charge Beaming	Model and experimentally verify charge transfer effectiveness
Inertial Thrusting during Charging	Develop inertial thrusting solution which provides minimal momentum and charge flux to the either craft
Robust Hybrid Relative Motion Control	Research relative hybrid (thrust/charge) relative motion control robust to charge and sensor model uncertainties
Charge Sensing	Explore and experimentally very methods to determine GLiDeR or debris charge and potential levels
Space Weather Impact	Examine worst-case space weather GLiDeR performance using particle-in-cell finite element plasma simulations





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Roadmap Overview

- The roadmap as it exists does a good job of surveying the space robotics/autonomy field and suggesting the next step evolutionary step and suggesting reasonable approaches to those
- The suggestions or goals may not be revolutionary or “game changing”, but that depends on how the reader interprets what the “next” step is.
- “Game changing” tend to come from what is not on the roadmap – new ways of looking at the problem that doesn’t use the current approach or even all the current infrastructure; by definition a game changing technology will bust the roadmap else it isn’t changing the game
- Advances should be tied to a mission and its needs, not a technology program for technology’s sake
  - Should think in terms of “we need to go do this thing and the only way to do it is to develop this new capability; how is that best done?”
  - To think otherwise is to make decisions based on what’s best for the bureaucracy, not for the agency’s mission
  - Need to let mission requirements define which parts of this roadmap take precedent
  - Unclear from roadmap graphic how well advances are tied to the missions

Back Up

Functional Requirements and Critical Parameter Ranges

Function	Performance parameter	Parameter range	Caveat
Sensing (of debris signatures)	Detection range	1500-13000 km	Standoff-range using meter-class telescope, varies with debris size.
	Track accuracy	6-30 km	Varies w/latency & update rates
	Spatial resolution	≤ 1 arcsec	Varies with turbulence, can be improved using compensation
	# req'd looks/acquisition time	3-100	Minimum of 3 to establish track. Max to estimate tumble rate.
	A priori info required	N/A	Ephemeris, initial orbit determination (IOD)
	Req'd data acquisition time	1 sec - 1 day	Minimum for prescreening, max for coarse track
	Latency of last look	< 1 orbital period to 1 day	Minimum for rendezvous, max for coarse track
Sensing (of inertial properties)	Accuracy of mass estimate	TBD	% of debris dry mass, critical mostly for Cat 3 debris requiring thrusters
	Center of mass accuracy	TBD	Proportional to max tolerable debris rotation rate
	Mass distribution accuracy	TBD	Bounded by pre-mission engineering design data
GNC	Orbital transfer Δv	TBD	Min per intercept, max per mission, requires orbital parameters
	Standoff range	200 m min, 2 km max	Min for prox ops, max for rendezvous
	Proximity range	2 m min, 200 m max	Min for precontact, max for collision avoidance
	Range error	5 cm min, 100 m max	Min at precontact, max at rendezvous
	Range rate error	2 mm/sec min, 10 cm/sec max	Min at precontact, max at rendezvous
	LOS rate error	TBD % of debris RPM	RPM range = 0-20 RPM
	Attitude	2 mrad min, 2° max	Min = attitude ref 1 σ per axis, max = tolerance at precontact
	Pointing	100 μrad	For pointing from 200 m to 2 m
Despin	Imparted torque	TBD	~ Torque to stop spin (0-20 RPM)
	Application force accuracy	~ 1% estimated	Minimize wrt debris mass within attitude controllability limits
Capture (grappling or harpoon)	Imparted thrust or impulse	~ 0.1 g	Limited by allowable debris reaction & wall thickness for harpoon
	Retention force limit	> 0.1 g	> thrust required to de-orbit within required decay period, depends on debris structural integrity
	Torque	120 Nm	Maximum torque to stop Ariane 5-size RSO tumbling at 45 deg/sec
	Tip velocity	< 15 cm/sec	Representative point design
	Tip position & rotation resolution	± 0.1 mm & ± 0.002 deg	Representative point design
	Control & visual servo bandwidths	> 1 Hz & >2 Hz	Similar to DARPA FREND specs
	Tracking accuracy	± 5 mm	Representative point design
Deorbit	Additional ballistic coefficient	TBD	Threshold to de-orbit within desired decay period given debris mass
	Duration of transfer op	TBD	Relative to # orbits, may be soft requirement
	Decay period	25 yrs	USG standard

Sensor Survey for Standoff and Proximity Operations

	Sensor/modality:	Applicability:	Advantages/Disadvantages:
Passive imaging	VIS/NIR	Standoff detection, tracking, prescreening	Compact, sensitive, high resolution, requires solar illumination, but readily accessible.
	MWIR/LWIR (with 2 or 3 colors)	Proximity inspection	Remote pyrometry, but more complex, and less resolution than VIS/NIR. No illumination req'd.
	Stereo imaging	Proximity inspection	Yields 3-D but requires two cameras or multiple looks with excellent fused GNC.
	Structured light	Proximity inspection	Yields 3-D but requires only one camera, offset illumination, and fused GNC.
	Polarization	Standoff prescreening	May help distinguish solar panels (specularity) & support prescreening. Adjunct to VIS/NIR.
	Low photon count	Standoff & proximity	Low SNR, virtually no illumination, high voltage.
	Multispectral	Standoff & proximity	May help discrimination of specific RSOs.
Lidar	Range-angle-angle	Proximity GNC and inspection	Yields 3-D but requires GNC inputs and accurate pointing for longer dwells.
	Range-Doppler	Standoff prescreening	Yields 3-D. May help characterization at longer ranges. Requires less pointing accuracy.
	Vibrometry	Near proximity prescreening	May determine RSO operational state beyond proximity ranges, but requires motion comp.
RF radar	Range-Doppler	Proximity imaging	May enable imaging if motion comp. is good, but requires a lot more mass & power.
	ISAR	Standoff imaging	Useful from the ground if motion state can be estimated independently.