**Sizing of "Mother Ship and Catcher" Missions for LEO Small Debris and for GEO Large Object Capture**

John B Bacon, Ph.D.
NASA Johnson Space Center

**Abstract**:
Most LEO debris lies in a limited number of inclination "bands" associated with specific useful orbits. Objects in such narrow inclination bands have all possible Right Ascensions of Ascending Node (RAANs), creating a different orbit plane for nearly every piece of debris. However, a low-orbiting satellite will always phase in RAAN faster than debris objects in higher orbits at the same inclination, potentially solving the problem. Such a low-orbiting base can serve as a "mother ship" that can tend and then send small, disposable common individual catcher/deboost devices--one for each debris object--as the facility drifts into the same RAAN as each higher object. The dV necessary to catch highly-eccentric orbit debris in the center of the band alternatively allows the capture of less-eccentric debris in a wider inclination range around the center. It is demonstrated that most LEO hazardous debris can be removed from orbit in three years, using a single LEO launch of one mother ship--with its onboard magazine of free-flying low-tech catchers--into each of ten identified bands, with second or potentially third launches into only the three highest-inclination bands.

The nearly 1000 objects near the geostationary orbit present special challenges in mass, maneuverability, and ultimate disposal options, leading to a dramatically different architecture and technology suite than the LEO solution. It is shown that the entire population of near-GEO derelict objects can be gathered and tethered together within a 3 year period for future scrap-yard operations using achievable technologies and only two earth launches.

# Sizing of
# "Mother Ship and Catcher" Missions
# for LEO Small Debris
# and for GEO Large Object Capture

John B. Bacon Ph.D.
NASA JSC/OM3
2101 NASA Parkway
Houston, TX 77058
John.bacon-1@nasa.gov
(281) 244-7086

# Release Approvals

- ***The contents of this presentation are in the public domain and may be used freely with appropriate citation.***

- ***The satellite catalog data contained herein has been approved for public release by:***
    - *HQ AFSPC/XOCS*
      *150 VANDENBERG ST. STE 1105*
      *PETERSON AFB, CO 80914-4220*

- ***The analyses contained herein have been approved for public release by NASA/JSC***

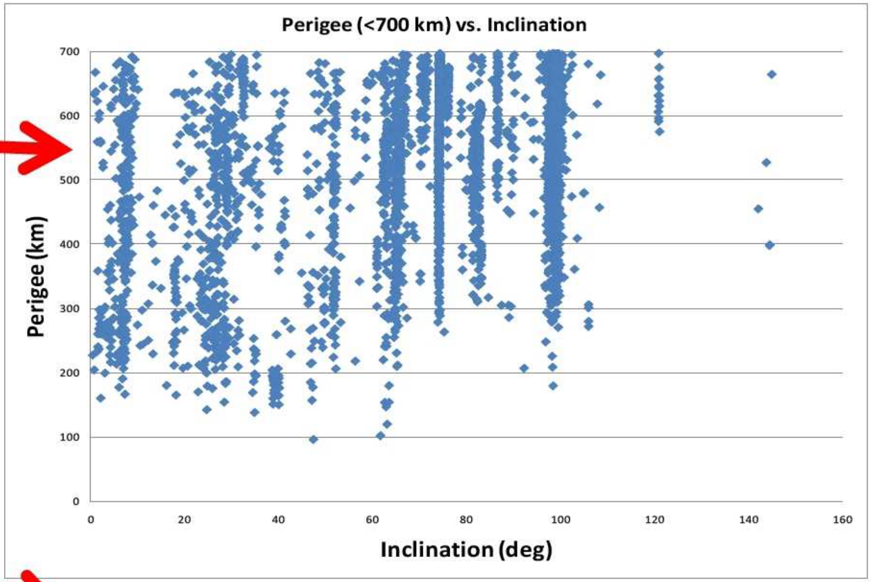
***john.bacon-1@nasa.gov 281 244-7086***

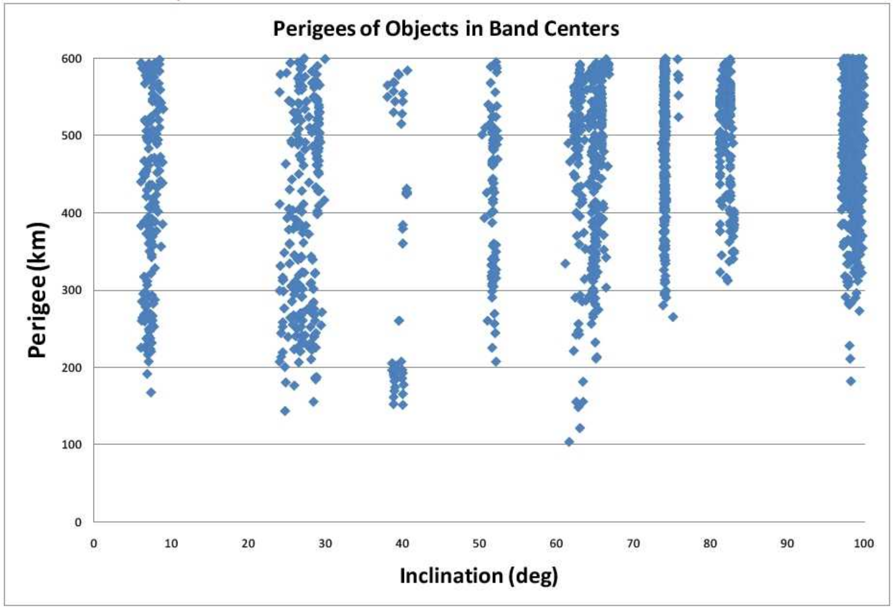
# *Outline:*

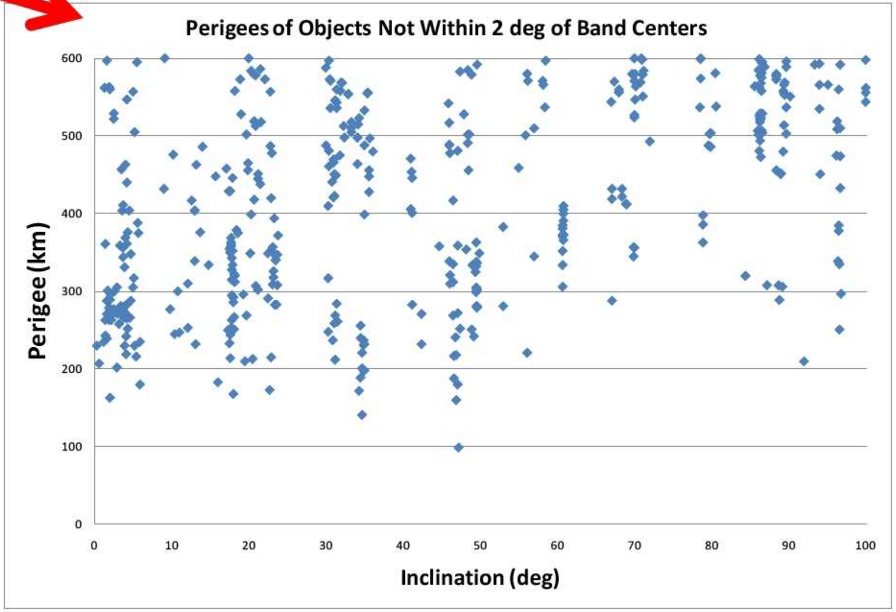
- *Characteristics of LEO Debris Inclination Bands*
- *Relative drift of orbital planes*
- *Rendezvous or Intercept?*
- *Reachable width of the debris band*
- *Post-capture flight plan and functions*
- *Mother-ship functions*
- *Special Case: GEO sizing*

# The Big Picture of LEO Debris Bands

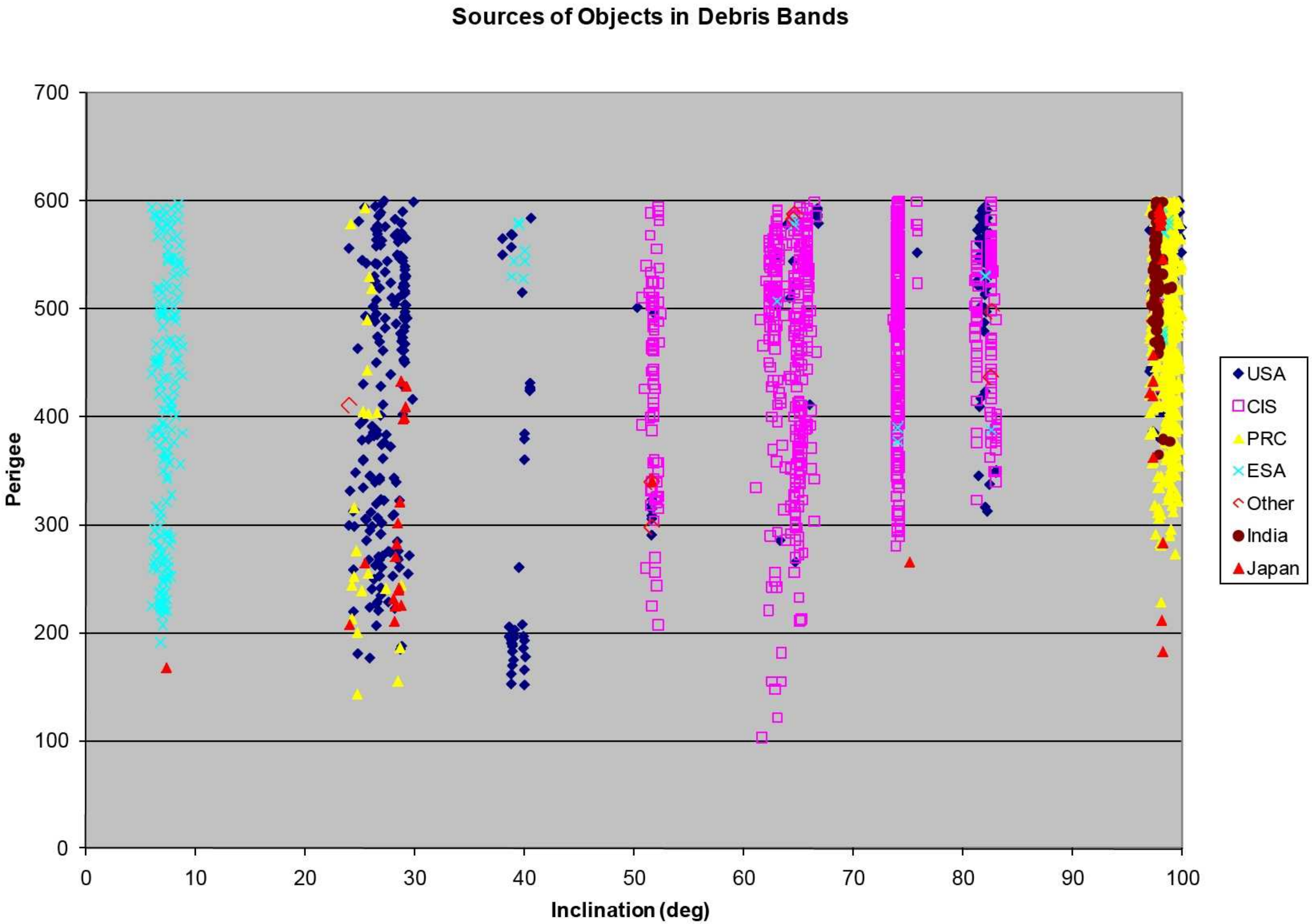
- ***Bands are evident in scatter plot of perigee vs. inclination***
- ***10 bands hold the major fraction of debris objects***
  - *Remainder is also banded*



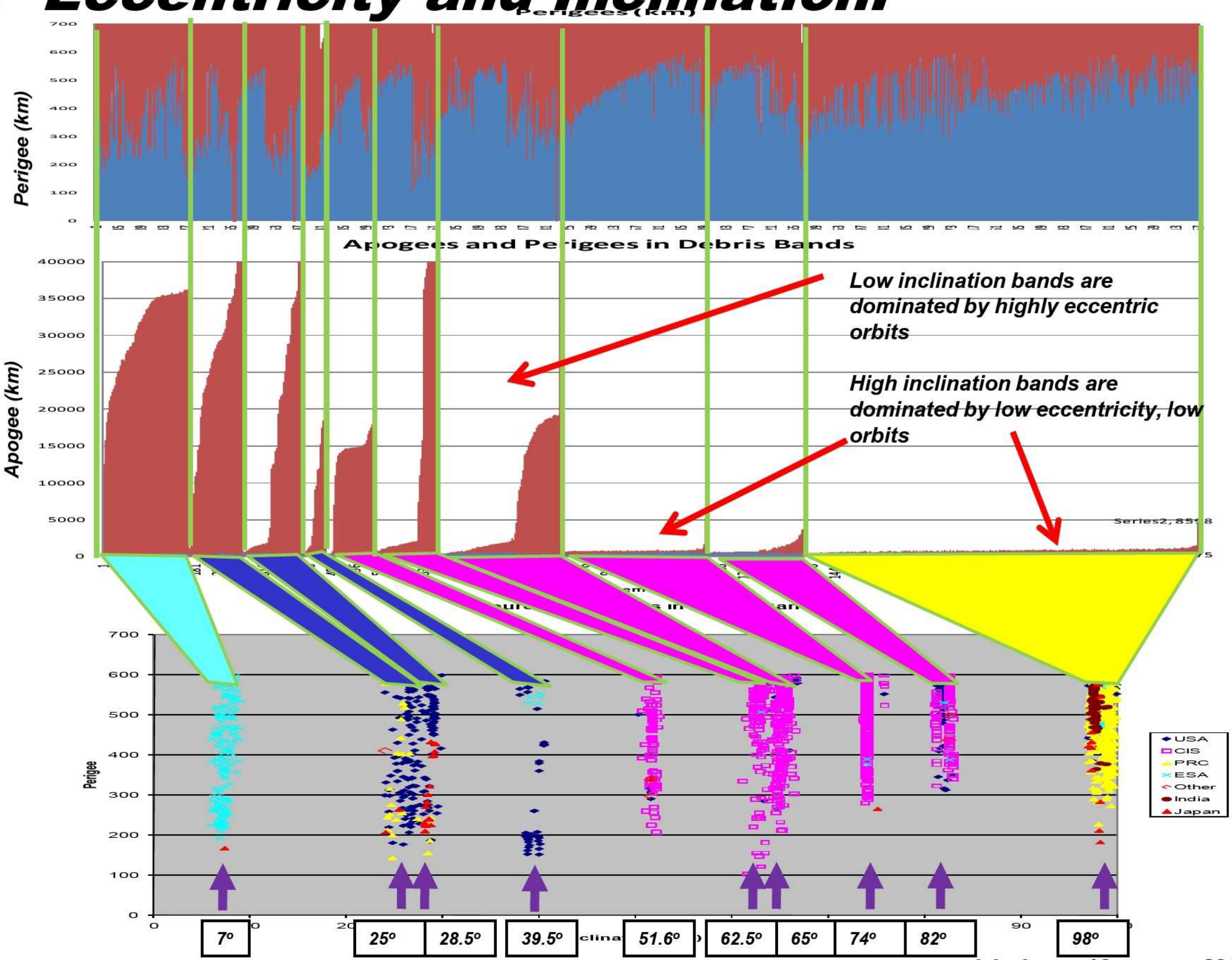



# Sources by Launch Nation:




*john.bacon-1@nasa.gov 281 244-7086*

# Eccentricity and Inclination:




john.bacon-1@nasa.gov 281 244-7086

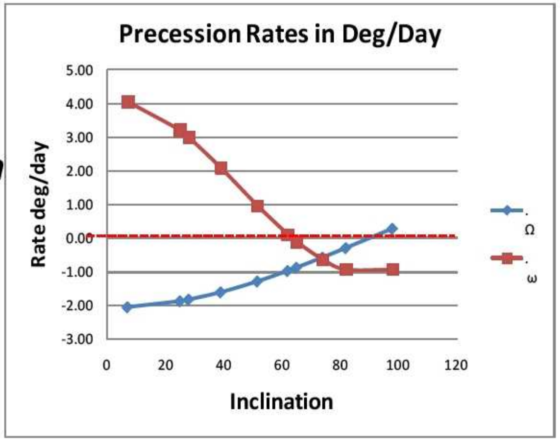
# Sizing the Catcher

- **Cost of catcher HW/Firmware is a mission cost driver**
  - **Cost of propellant is <u>negligible</u> as long as resulting mass budget does not challenge required performance of HW/firmware.**
    - ☞ *Cheap and dumb HW is preferable to light and expensive, up to a point.*
    - ☞ *Prefer catcher net cost <$1000 USD each.* *(=$13.2M for catchers for **<u>all</u>** LEO tracked debris)*
- **Prefer one mother ship per inclination band**
  - **second largest cost driver is the launcher.**
  - **(Launcher capability)/(number of objects in band) is thus a major sizing determinant.**
- **How many can we catch?**
  - **Rocket equation for 3000 m/sec:**
    - ☞ *Mf/Mo= EXP(-3000/g*ISP) ~ 22% for **<u>200 ISP monopropellant</u>**.*assume monopropellant for design simplicity/weight*
    - ☞ *A 10 kg initial mass catcher can have **2.2 kg** of infrastructure & payload at capture in this scenario*
    - ☞ *A comprehensive satellite can be packaged in this sort of mass.*
  - **After optimizing prop loading per object, 13200 objects can be caught* from 10 "mother ships" at this dry catcher mass.**
    - ☞ **Immediate propulsive de-orbit is possible for many (but not all) objects.*
    - ☞ **Drag enhancement to accelerate natural decay is a solution for large debris objects*

**john.bacon-1@nasa.gov 281 244-7086**

# Fast Intercept or Slow Catch?

- ***<u>High eccentricity</u> dominates the long-duration population***
  - ***Small inclination differences within the band add quickly to required dV***
- ***RAAN and Mean Anomaly precess at a <u>fixed</u> ratio for any inclination***




$$\dot{\Omega}_{J2} = -2.06474 * 10^{14} \underline{\underline{a^{-7/2}\left(1-e^2\right)^{-2}}} \cos(i)[\deg/\, day]^*$$

$$\dot{\omega}_{J2} = +1.03237 * 10^{14} \underline{\underline{a^{-7/2}\left(1-e^2\right)^{-2}}}\left[4-5\sin^2(i)\right][\deg/\, day]^*$$

** from Larson and Wertz, Space Mission Analysis and Design (1992) p141*

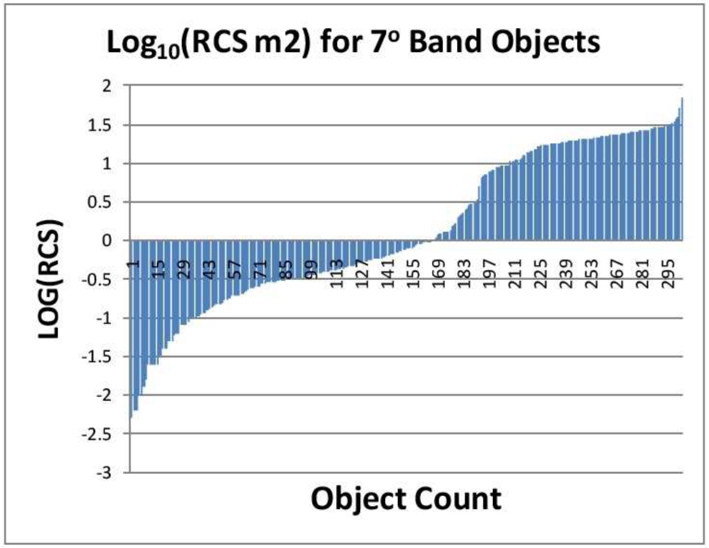
- *Cannot simultaneously solve the mother ship solution for hundreds of target objects*
  - *Particularly near 63.43 deg where mean anomaly is stationary*
- *Therefore, must <u>circularize</u> the mother ship orbit, and launch catcher into co-elliptic elliptic orbit for best use of dV budget and minimum time-of-mission*
- *Generally, better for mass budget and mission duration to launch mother ship to as low as possible circular orbit, and make up dV difference with catchers.*

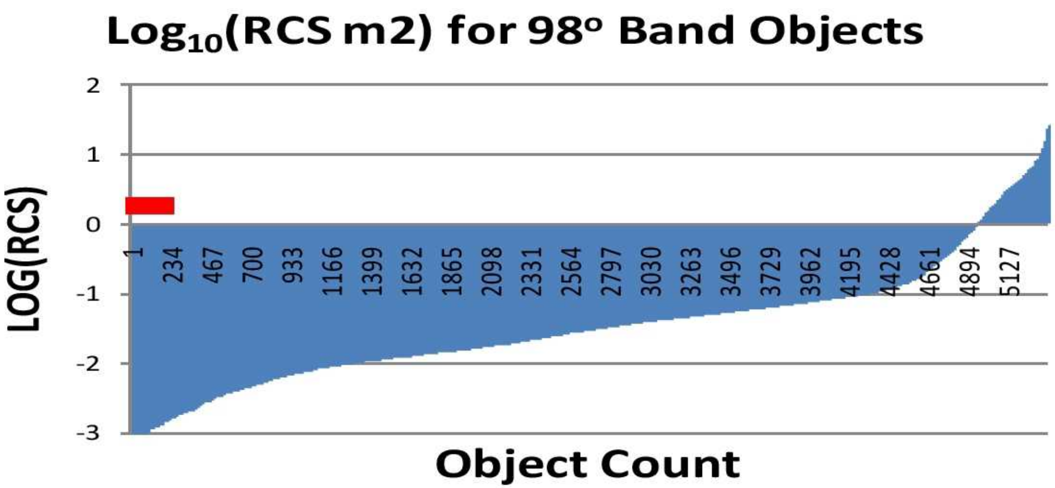
- ***Delta-Vs associated with intercept from low-circular are many km/sec***
- ***Safe capture is crucial: sizing/strengths of capture system and precise high-speed targeting dominate the mass budget and complexity/risk in "intercept" scenarios***
- ***To simplify and lighten the catcher and to avoid export control issues, a low relative velocity is necessary (==Slow Catch)***
  - ***May as well rendezvous***
  - ***Small prop reserve budget provides ballistic margin for timing, repeat attempts, and often for immediate debris de-orbit.***

***john.bacon-1@nasa.gov 281 244-7086***

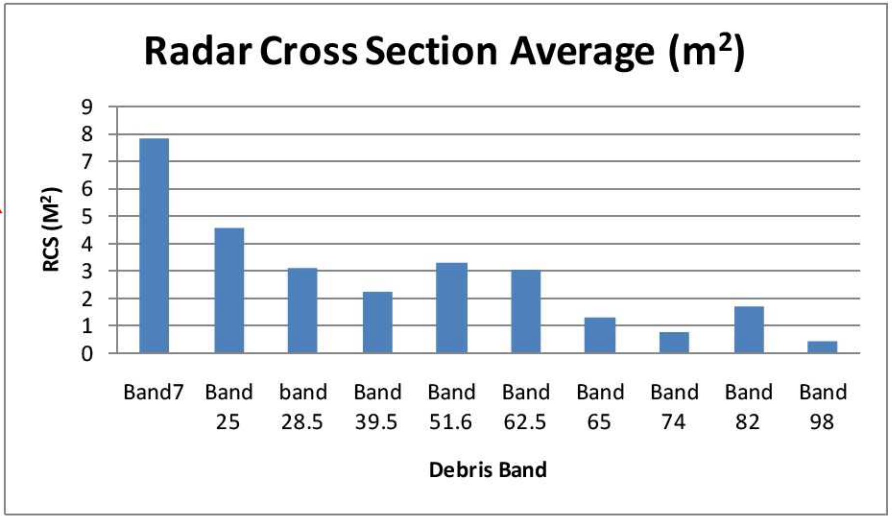
# *Size Distribution in Bands*

## *(Radar Cross Section is surrogate for size: $Log_{10}$(RCS ) plotted)*




*Size distribution moves from larger to smaller as inclination increases*




*john.bacon-1@nasa.gov 281 244-7086*

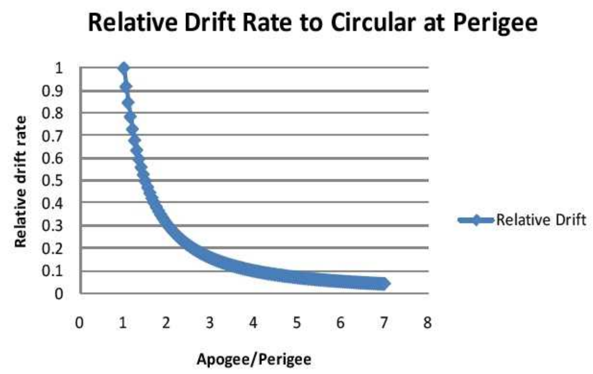
# Phasing Rate

$$\dot{\Omega}_o = -2.06474 * 10^{14} a_o^{-7/2} \cos(i)\left(1 - e_o^2\right)^{-2} [\deg/ day]^*$$

$$\dot{\Omega}_{relative} = -2.06474 * 10^{14} \cos(i) * \left[a_1^{-7/2}\left(1 - e_1^2\right)^{-2} - a_o^{-7/2}\left(1 - e_o^2\right)^{-2}\right]$$

** from Larson and Wertz, Space Mission Analysis and Design (1992) p141*

- ***At any higher orbit $a_1 > a_o$ (especially with higher eccentricity) an object's absolute phase rate compared to a lower circularized-orbit object ($a_o$) will be asymptotically closer to zero, and differential drift rate approaches $\dot{\Omega}_o$***

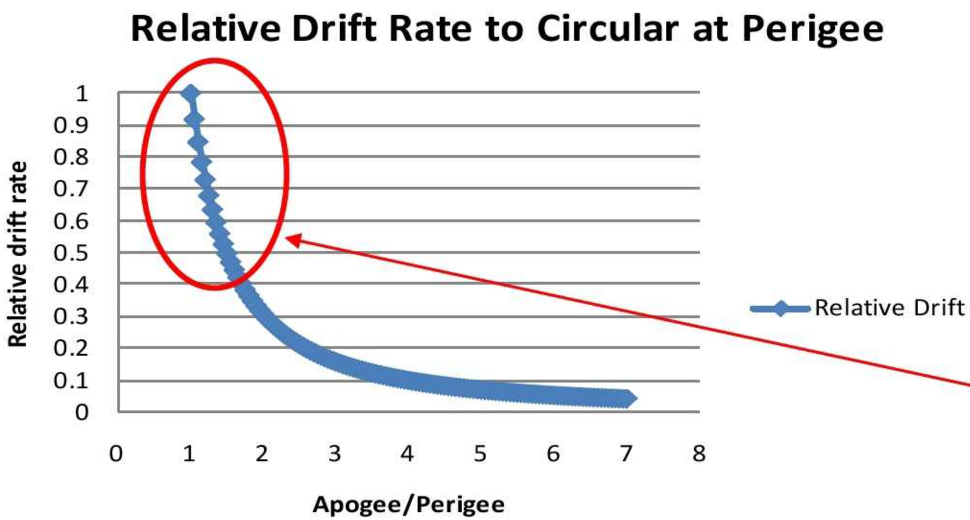



- ***Because of differential drift, the orbit planes of the debris object and of the lower mother ship slowly move through periodic alignment***

*john.bacon-1@nasa.gov 281 244-7086*

# *Differential Phasing Rate*

- ***Slow phase rates & small altitude differences at high inclinations may demand <u>additional missions to rotated orbit planes to shorten program duration</u>***
- ***Particularly useful move considering quantities of high-inclination objects***

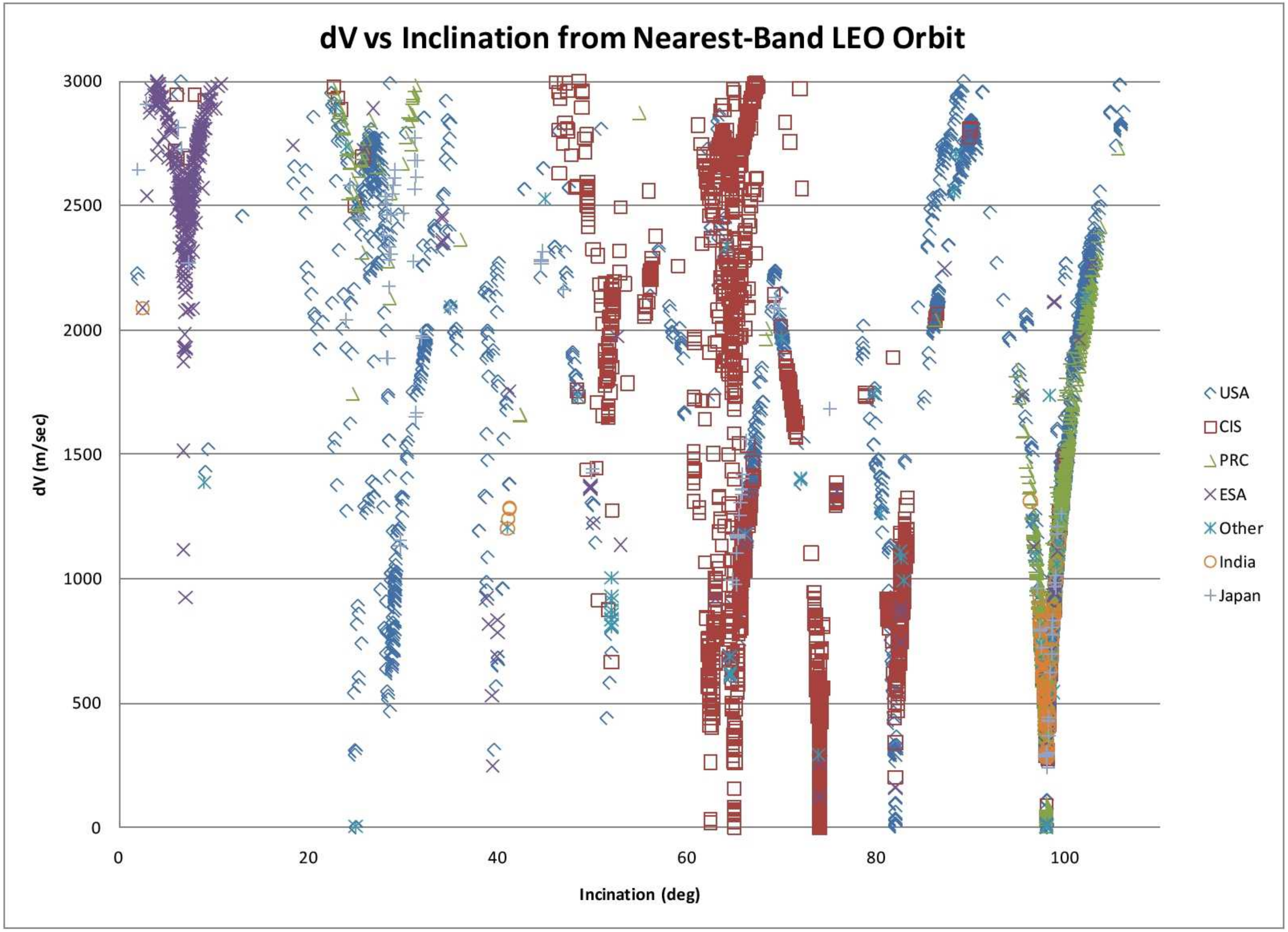



| Band Center | $\dot{\Omega}$ | $\dot{\omega}$ | Years to Lap 360 Deg |
|---|---|---|---|
| 7 | -2.05 | 4.05 | 0.48 |
| 25 | -1.87 | 3.21 | 0.53 |
| 28 | -1.82 | 2.99 | 0.54 |
| 39 | -1.60 | 2.09 | 0.61 |
| 51.6 | -1.28 | 0.96 | 0.77 |
| 62 | -0.97 | 0.11 | 1.02 |
| 65 | -0.87 | -0.11 | 1.13 |
| 74 | -0.57 | -0.64 | 1.73 |
| 82 | -0.29 | -0.93 | 3.43 |
| 98 | 0.29 | -0.93 | 3.43 |

*john.bacon-1@nasa.gov 281 244-7086*

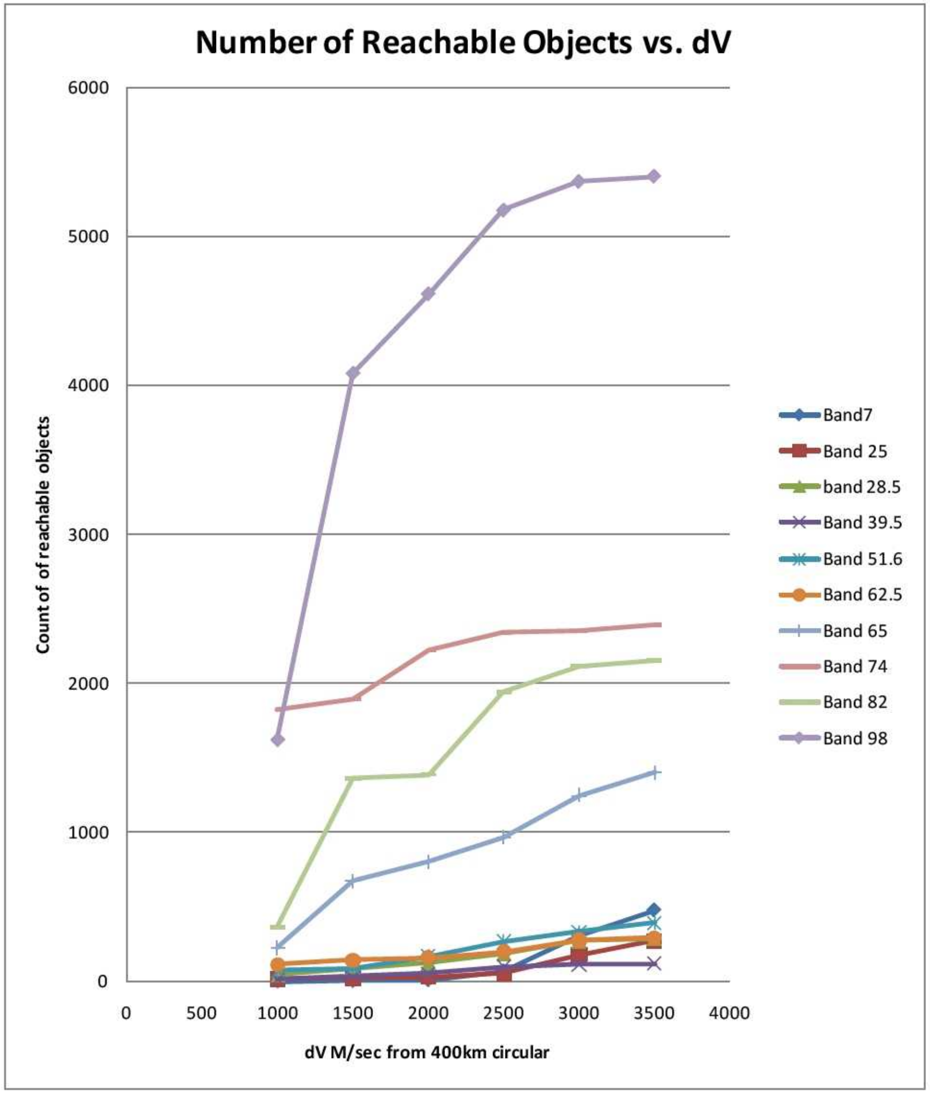
# High dV Allows Wider Bands

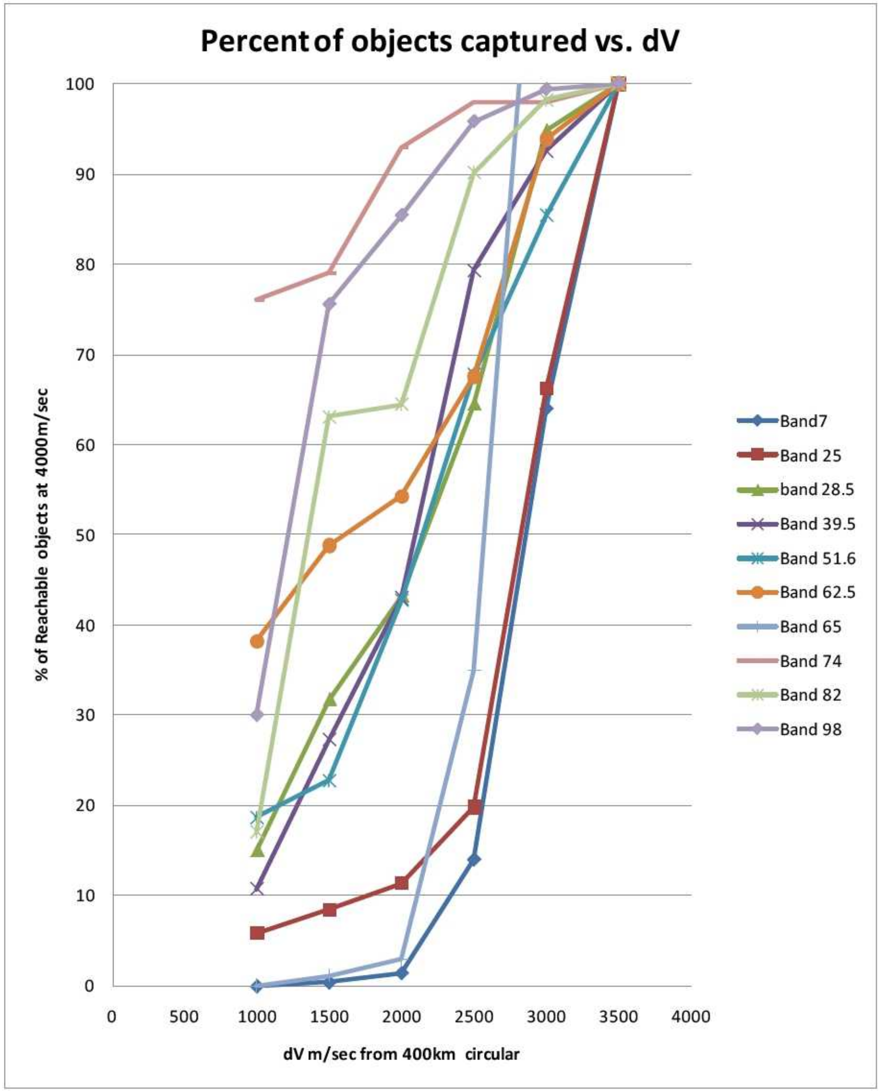
## (lower out-of-plane objects reachable, as well as higher in-plane objects)




john.bacon-1@nasa.gov 281 244-7086

# Band Populations & Capture dV




john.bacon-1@nasa.gov 281 244-7086

# *Prop Budget for Common Catchers*

- ***Can implement <u>variable</u> tank sizes for common engine and payload***
- ***Typical sizing mix for common 2.2 kg payload shows that a <u>common</u> total 10Kg catcher works in launcher mass budget for SIX inclination bands.***
- ***High debris quantities at other inclinations need variable prop loads, smaller catcher payload, or <u>more mother-ship missions</u>***
- ***<u>$25^0$ & $28.5^o$ band pair may be clearable with a single launch.</u>***

**<u>2-Bucket</u>** Prop and Catcher Masses (kg) for dV from 400 km Circular

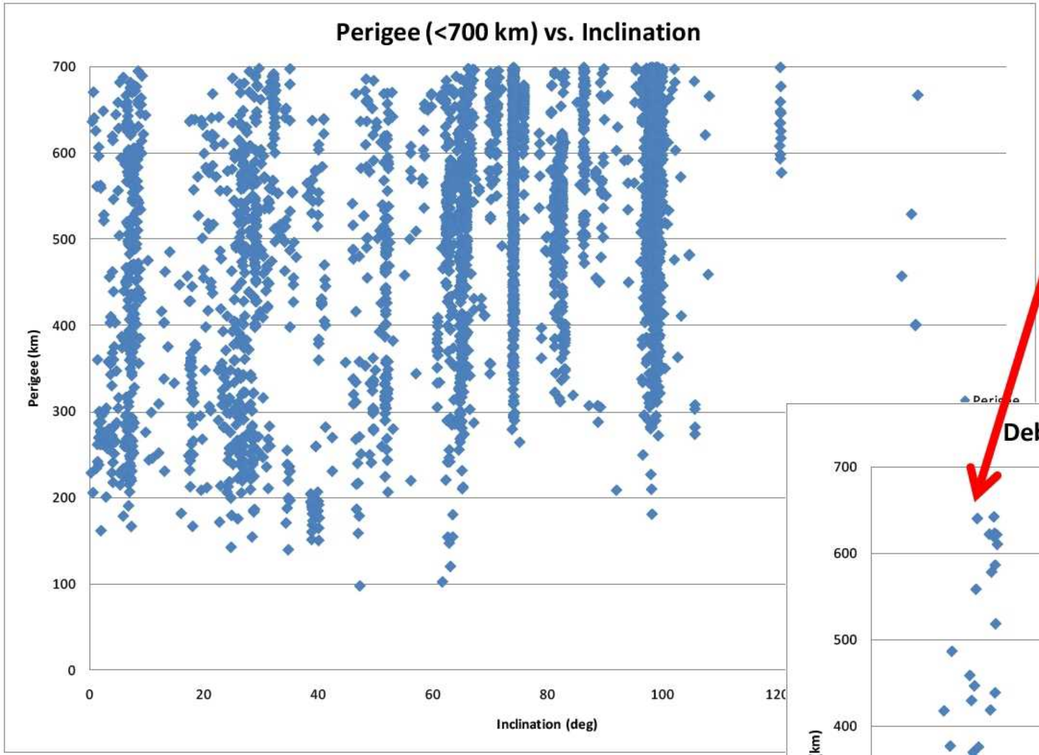
| QTY> | 0-1000 m/sec | 1000-1500 m/sec | 1500-2000 m/sec | 2000-2500 m/sec | 2500-3000 m/sec | 3000-3500 m/sec | Total Prop 2.2kg payloads T<2 | Total catchers | Total Catcher & Prop |
|---|---|---|---|---|---|---|---|---|---|
| Band7 | 0 | 2 | 5 | 60 | 238 | 172 | 5186 | 1049 | 6236 |
| Band 25 | 1 | 7 | 8 | 23 | 126 | 92 | 2957 | 598 | 3556 |
| band 28.5 | 2 | 48 | 33 | 61 | 87 | 15 | 3120 | 631 | 3752 |
| Band 39.5 | 3 | 20 | 19 | 44 | 16 | 9 | 815 | 266 | 1081 |
| Band 51.6 | 4 | 16 | 78 | 98 | 69 | 57 | 2869 | 860 | 3729 |
| Band 62.5 | 5 | 31 | 16 | 39 | 77 | 18 | 3186 | 645 | 3830 |
| Band 65 | 6 | 446 | 129 | 165 | 281 | 153 | 10189 | 3082 | 13271 |
| Band 74 | 7 | 72 | 333 | 120 | 3 | 47 | 5630 | 5161 | 10791 |
| Band 82 | 8 | 993 | 29 | 553 | 175 | 38 | 11181 | 4657 | 15838 |
| Band 98 | 9 | 2456 | 532 | 561 | 192 | 35 | 20488 | 11805 | 32293 |

**<u>6-Bucket</u>** Prop and Catcher Masses (kg) for dV from 400 km Circular

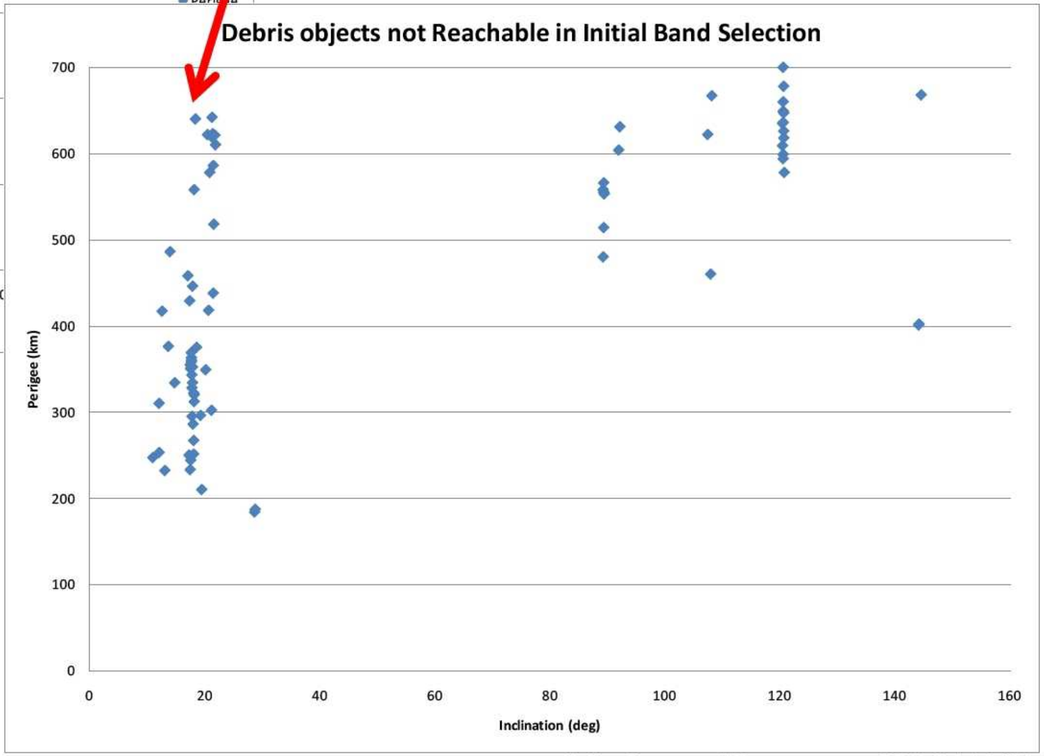
| Prop> | 0-1000 m/sec | 1000-1500 m/sec | 1500-2000 m/sec | 2000-2500 m/sec | 2500-3000 m/sec | 3000-3500 m/sec | Total Prop 2.2kg payloads T<6 | Total catchers | Total Catcher & Prop |
|---|---|---|---|---|---|---|---|---|---|
| Band7 | 0 | 5 | 19 | 339 | 1888 | 1870 | 4122 | 1049 | 5172 |
| Band 25 | 1 | 18 | 31 | 130 | 1000 | 1000 | 2180 | 565 | 2746 |
| band 28.5 | 3 | 121 | 128 | 345 | 690 | 163 | 1451 | 541 | 1992 |
| Band 39.5 | 4 | 50 | 74 | 249 | 127 | 98 | 602 | 244 | 847 |
| Band 51.6 | 6 | 40 | 303 | 554 | 547 | 620 | 2071 | 708 | 2780 |
| Band 62.5 | 7 | 78 | 62 | 221 | 611 | 196 | 1175 | 409 | 1584 |
| Band 65 | 9 | 1125 | 502 | 933 | 2230 | 1664 | 6462 | 2596 | 9058 |
| Band 74 | 10 | 182 | 1296 | 679 | 24 | 511 | 2701 | 1280 | 3981 |
| Band 82 | 12 | 2504 | 113 | 3128 | 1389 | 413 | 7559 | 3951 | 11510 |
| Band 98 | 13 | 6194 | 2070 | 3173 | 1523 | 381 | 13354 | 8327 | 21681 |

***john.bacon-1@nasa.gov 281 244-7086***

# Before and After




*Band near 17 deg inclination is tempting next target*



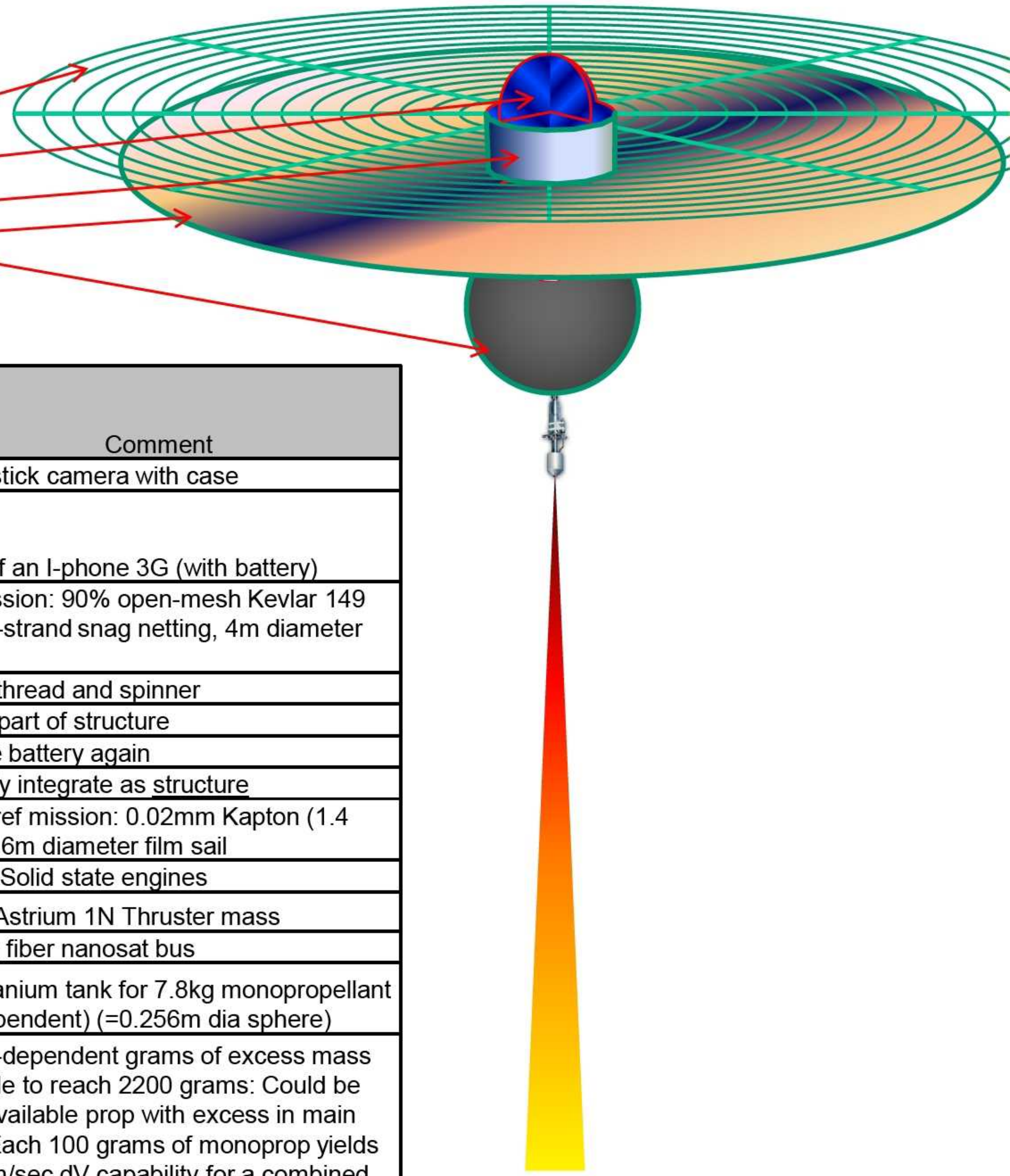

*john.bacon-1@nasa.gov 281 244-7086*

# ***Summary in LEO:***

- ***<u>Low inclinations</u> have:***
  - ***high eccentricity,***
  - ***low counts***
  - ***Larger radar cross section***
  - ***Rapid differential phasing***
- ***Single mission with single magazine of high dV catchers should work for most objects***
- ***Drag-assisted de-orbit is probable removal mechanism for half of captured objects***
- ***Propulsive de-orbit is possible for remainder***
- ***<u>High inclinations</u> have:***
  - ***low eccentricity,***
  - ***high counts***
  - ***Smaller radar cross section***
  - ***Slow phasing***
- ***<u>Probable</u> need for multiple missions to same band***
- ***<u>Potential</u> need for multiple prop load variants on one mission***
- ***Propulsive de-orbit is practical for most captured objects***

## Typical Catcher Reference Concept:

**Kevlar® snag web**
**Retroreflector/solar cells/net containment**
**Avionics with MEMS thruster/antenna shell**
**Kapton® Drag Sail (post capture)**
**Tank with main thruster below**



| Item | Typical Mass (g) | Comment |
|---|---|---|
| Tracking sensor | 90 | BW lipstick camera with case |
| Integrated circuitry: send-receive, transponder,attitude control, system control, video processing | 133 | Mass of an I-phone 3G (with battery) |
| Capture mechanism | 185 | Ref mission: 90% open-mesh Kevlar 149 0.1mm-strand snag netting, 4m diameter web |
| Cinching mechanism | 50 | Kevlar thread and spinner |
| Laser/Radar retroreflector | 20 | Mostly part of structure |
| Local short-duration power source | 133 | I-phone battery again |
| Small recharge photocell | 60 | Possibly integrate as structure |
| Drag enhancement | 400 | Sizing ref mission: 0.02mm Kapton (1.4 g/cm3) 6m diameter film sail |
| Attitude control | 200 | MEMS Solid state engines |
| Main thruster | 290 | EADS/Astrium 1N Thruster mass |
| Structure | 100 | Carbon fiber nanosat bus |
| Tankage | 100 | Max titanium tank for 7.8kg monopropellant (dV-dependent) (=0.256m dia sphere) |
| Post-capture Propellant capability | 439 | Margin-dependent grams of excess mass available to reach 2200 grams: Could be more available prop with excess in main tank. Each 100 grams of monoprop yields 19.64 m/sec dV capability for a combined 10kg catcher/captured object |
| | | |
| | **2200** | **Total** |

***john.bacon-1@nasa.gov 281 244-7086***

# *Useful Features: Mother Ship ~5,000-10,000kg*

- *3-axis gyro-stable control*
- *Magazines of (varying) dV catchers*
- *Debris shields (to protect the many "eggs still in the nest")*
- *(strong) Laser to illuminate target*
- *Solar power*
- *Doppler Radar (to track catcher)*
- *Accurate on-board ephemerides for self and targets*
- *Very high ballistic number (for long duration low orbit)*
- *Potentially an electric spinner/lateral launcher*
  - *to launch catchers symmetrically out-of plane*
  - *Greatly expands inclination width of band for no additional prop*

*john.bacon-1@nasa.gov 281 244-7086*

# *SPECIAL CASE:*
# *GEO Derelict Object Capture*

# *GEOSTATIONARY Case*

- ***Predominantly large (spent) objects***
  - ***1000-2000kg, or often much more***
  - ***Specialized catchers are more useful for recovery option***
- ***Common altitude (35786 km)***
  - ***De-orbit not practical***
- ***Common orbit inclination (0)***
- ***Derelict objects using valuable space***
- ***Retired objects within only a few m/sec of GEO***
  - ***Use orbit period rather than plane precession to accomplish phasing/rendezvous***

*john.bacon-1@nasa.gov 281 244-7086*

*The Ride of the Valkyries by John Charles Dollman (Published in 1909: before 1923 so public domain in the United States. Artist died in 1934 so public domain in Britain)*

# *WOTAN and Valkyries*

- ***WOTAN==special variant of the Mother Ship***
- ***Valkyries==special Catcher variants***

- ***Both optimized for large objects near GEO***
  - ***Designed for rendezvous, stabilization, collection, and manipulation of large uncooperative objects***

- ***4 Useful missions in one:***
  - ***Clean explosion hazards and derelicts from Clarke orbit region***
  - ***Demonstrate space mining/asteroid capture techniques***
  - ***Consolidate and transfer upwards a highly-valuable resource depot, already very high in the gravity well***
    - *(62% of Earth-escape dV)*
  - ***Develop worldwide cooperative space mission***
    - *Military/Proprietary nature of many target objects requires special security attention*

*john.bacon-1@nasa.gov 281 244-7086*

# Valkyries

- Mythical riders who carried dead from battlefield to a useful afterlife
- MUCH more massive and capable "catchers" than used in LEO
- Grapple-able free-flyers
  - with interchangeable arms and robust effectors specialized to snare/despin/retain each class of object
  - Likely Ion/Plasma Engine for fuel budget constraint
  - Implies High Power/weight requirement:
    - Probably receive beamed power from WOTAN and/or ground
  - Refuelable at WOTAN berthing station
  - Video link for tele-robotic control during rendezvous and capture
  - Approximately large-trash-can sized.
  - 10-20 of them aboard.

john.bacon-1@nasa.gov 281 244-7086

# *WOTAN*

- ***Overlord of the Valkyries and of all others below***
  - ***<u>W</u>orldwide <u>O</u>rbit <u>T</u>ransfer of <u>A</u>ssets <u>N</u>exus****
    - **nex·us (nkss) n. pl. **nexus** or **nex·us·es***
      ***1.** A means of connection; a link or tie: "this nexus between New York's . . . real-estate investors and its . . . politicians" (Wall Street Journal).*
    - ***2.** A connected series or group.*
    - ***3.** The core or center: "The real nexus of the money culture [was] Wall Street" (Bill Barol).*
      - *The American Heritage® Dictionary of the English Language, Fourth Edition*

- ***Drifting 1 m/sec above GEO***
  - ***24 km above functioning satellites***
  - ***Retrograde drift once around planet every 3 years***

- ***Berthing/Refueling and communications relay base for Valkyries.***

- ***Tele-robotic transfer and attachment of recovered satellites, clipped to a sturdy spooled tether (~5 km for 5m/object, ~1000 objects)***
  - *KEVLAR® 149 3mm-diameter stranded cable weighs 53 kg, with 133 tonnes tensile strength.*

- ***Large power capability for high ISP arc-jet propulsion***
  - ***Beamed up or self-generated (solar or nuclear).***
  - ***Valkyries supply the plasma engines on ride upwards***
  - ***Convert power to energy beam towards free-flying Valkyries in harvest mode***

- ***Strong shielding for spiral transit up to GEO+***

- ***Gyro stabilization***

***john.bacon-1@nasa.gov 281 244-7086***

# *Mission Scenario: Pre-Harvest*

- *20,000+kg WOTAN Mother-ship with Valkyries to near-equatorial LEO (includes 8000 kg prop)*
- *20,000+kg "dumb" propellant tank to coplanar orbit*
- *Valkyrie dispatched to capture and retrieve prop tank*
- *Robotic mechanical- and fluid-attachment of prop tank to WOTAN*
- *Slow spiral transfer to GEO with 3000+sec ISP solar-powered arc-jet*
  - *Valkyries supply the engines*
  - *Valkyries (and catchers) dispatched to debris targets of opportunity during journey.*
  - *~8000 kg propellant used @ 3000 ISP for LEO-GEO transfer*
  - *~20,000kg prop available at GEO for recapture ops*
    - *also @ 3000 ISP*

*john.bacon-1@nasa.gov 281 244-7086*

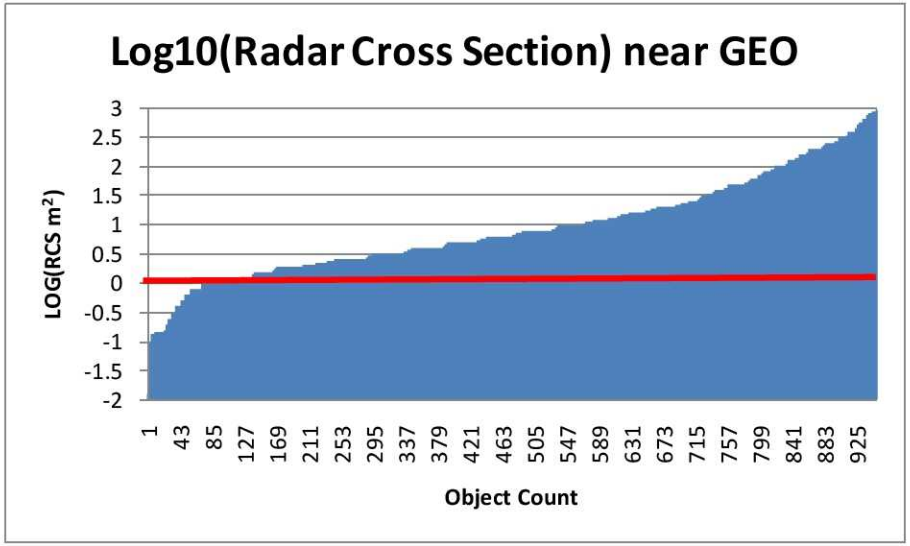
# Mission Scenario: Harvest

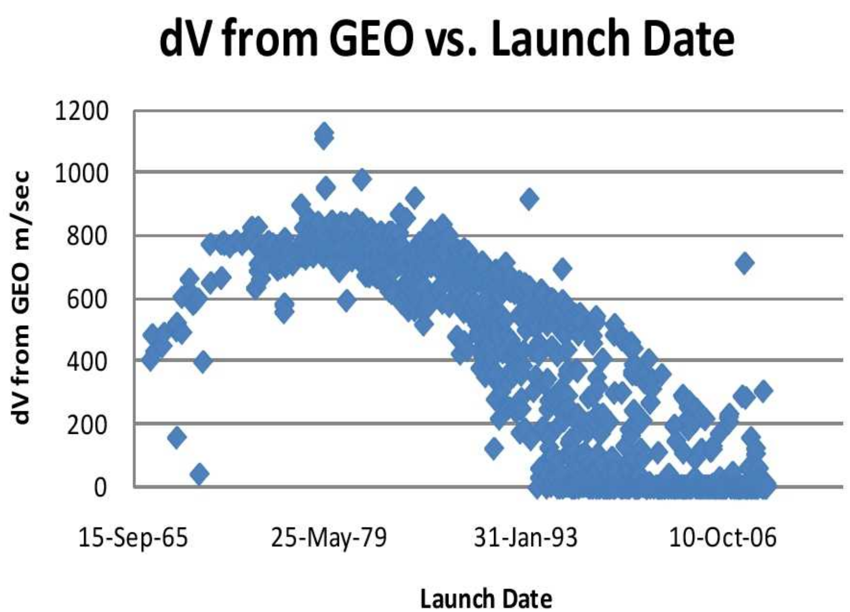
- *Valkyrie outfitted with object-specific capture effector and fueled at berthing station on WOTAN*
- *Valkyrie dispatched to tele-robotically capture, de-spin, and retrieve GEO object*
- *WOTAN tele-robotic capture of free-flying Valkyrie with attached retrieved object*
- *Tele-robotic attachment of tethering clips to retrieved object*
- *Tele-robotic object transfer to WOTAN with subsequent object attachment to tether*
- *Robotic berthing of Valkyrie to refueling/sustenance port*
- *(TBR: Beginning of scrap-rendering depot operations)*
  - *Especially jumpering of retrieved power systems to common supplemental power bus*
  - *Probably wait until post-departure from Clarke orbit region for any disassembly/consolidation ops.*

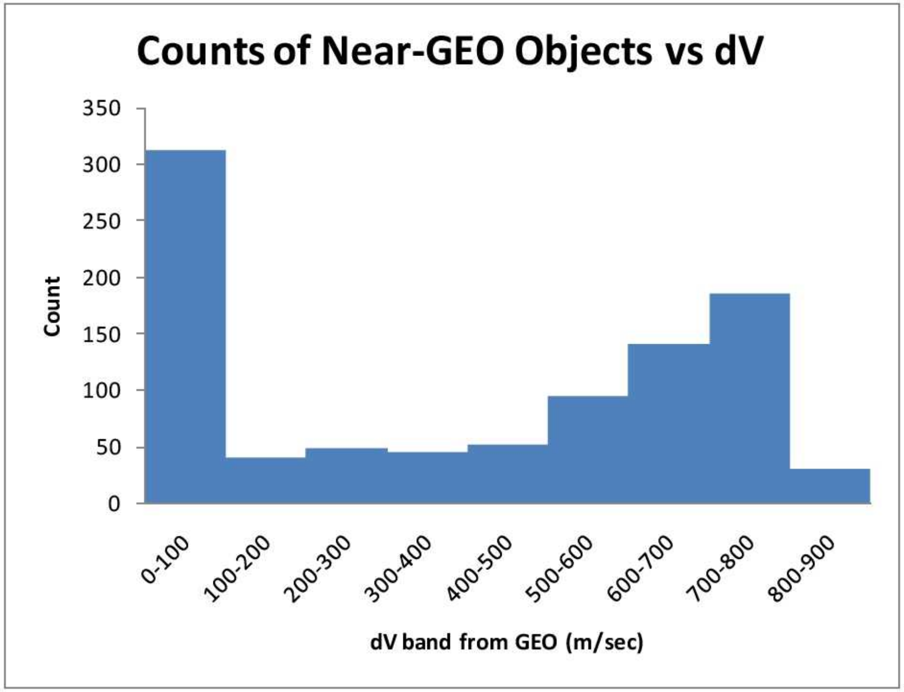
john.bacon-1@nasa.gov 281 244-7086

# Near-GEO Objects

- 938 published objects
  - Large RCS
  - estimated average mass 1000 kg each
- Half within 400 m/sec of Geostationary
  - ~ All of the dV is related to inclination change.




john.bacon-1@nasa.gov 281 244-7086

# ***Mass Budget:***

- ***20,000kg  prop at 3000 ISP provides maximum $6*10^8$ kg*m/sec***
  - *At ~1000kg/object, ~400 m/sec average delta V, and ~1000 objects, this is enough dV to capture most objects, with a ~150-kg Valkyrie*

- ***~10 Valkyries =1500 kg  (results in ~20-day retrieval cycle per object, 1 object/day for 3 years)***

- ***WOTAN  =20,000kg LEO insertion***

  ***-   8,000kg Prop to spiral up***

  ***-   1.500 kg for 10 Valkyries***

  ***= 10,500 kg for WOTAN***

***john.bacon-1@nasa.gov 281 244-7086***

# *Mission Scenario: Post-Harvest*

- *__Valkyries dispatched back to LEO__ to capture and retrieve prop tanks (with power)*

- *Valkyries bring staged prop and increasing power farm to GEO+ rendezvous with WOTAN*

- *Robotic attachment of fresh prop tank to WOTAN*
  - *Used tanks to the tether*

- *Slow spiral Earth departure and Lunar or Mars transfer with 3000+sec ISP solar-powered arc-jet*

- *Depot/scrap recovery operations begin.*

*john.bacon-1@nasa.gov 281 244-7086*

# *Conclusion*

- ***~<u>13200 objects in LEO can be removed</u> in 3 years with approximately 12 heavy-lift launchers***
  - ***Most of the cost is expected to be in the operations, launchers, and integration of the "mother ships"***
  - ***Mass produced mono-prop low-ISP "catchers" (2.2kg dry, 10 kg wet) are the cheap part.***
    - *($26M @ $2000 USD Each)*

- ***<u>All debris near GEO can be removed</u> in a 3-year mission using 2 heavy-lift launches***
  - ***Scrap yard would weigh 3x mass of ISS and can be easily propelled further out to alleviate raw materials needs in future exploration.***
  - ***Reusable 150 kg ion-drive "Valkyrie' catchers are the key***

*john.bacon-1@nasa.gov 281 244-7086*

# Backup

john.bacon-1@nasa.gov 281 244-7086

# Net sizing

- **Kevlar® 149:**
  - **1.47 g/cm3**
  - **Assume 4 m diameter web, of 0.1mm fiber 90% open mesh**
    - 23N per fiber tensile strength (3 GPa tensile strength)
    - Vol= $\pi$*(200cm)$^2$*(0.01cm)*(0.1solid fraction)
      - = 785 $cm^3$
  - **186 GPa tensile Modulus**
  - **2% elongation**

john.bacon-1@nasa.gov 281 244-7086