Refueling Orbital Navigator (RON)
for Active Debris Removal, and Asset Relocation, Recovery and Repair

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Space Propulsion 101

Ideal Rocket Equation: $$\Delta V = I_{sp} g_0 \ln \frac{M_i}{M_f}$$

How Do We Beat It?

Propellantless propulsion
(Infinite Isp)

Large Deployable Structures
Tethers
Gossamer structure

Problems with deployment, stability, lifetime

We can get propellant for "free"

Air Breathing

Requires:

- ✓ **Low drag spacecraft**
- ✓ **High collection efficiency**
- ✓ **High Isp, high efficiency thruster**

Refueling Orbital Navigator (RON)

RON can provide for -

- Active Debris Removal (ADR)
- In Situ Resource Utilization (ISRU)
- Air-breathing Orbital Transfer Vehicle (AOTV)

Elliptical Collection Orbit (ECO):

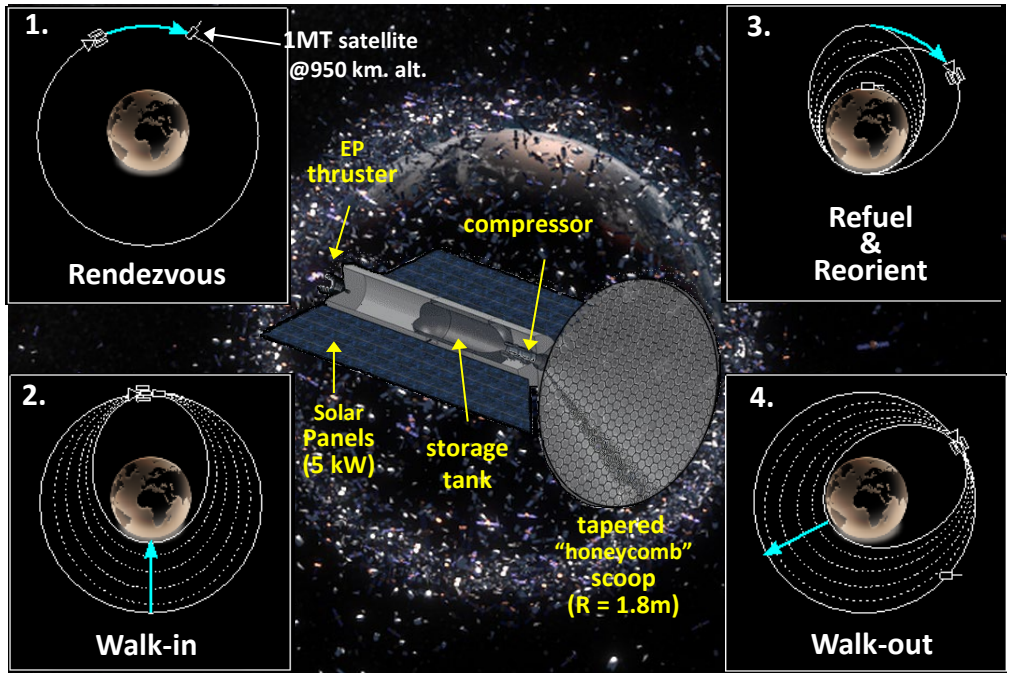
- ECO enables refueling at minimal drag
- Substantial reduction in power requirements

Refuellable:

- Significantly less launch weight
- Subtantially longer mission Life

Orbital Navigator:

- Process 550 kg of propellant/yr.
- 85 Deg. inclination change/yr.
- 100,000 m/s Delta-V/yr.



Benefits & Potential

- Large space debris removal
- non-Keplerian orbits
- rapid continuous plane changes
- ultra low flyby approaches
- Asset relocation with changing objectives
- Disabled satellite capture for in-space repair

- RON promises to be an AOTV that overcomes many of the hurtles of an airbreathing space propulsion system
- RON's mission architecture needs only a fraction of power and size assumed before
- RON would enable a new class of missions

Classic Air-breathing Orbit

Assume 150 km Orbit
$\Rightarrow$ 10 m^2 scoop, Drag is 1.23 N

$$T_{EP} = \frac{2\eta P}{I_{sp} g_o}$$

50% efficient, 2000s Isp Thruster
30 kw for Drag make-up



At 366 W/m^2 Solar panel
82 m^2 need for sustained flight

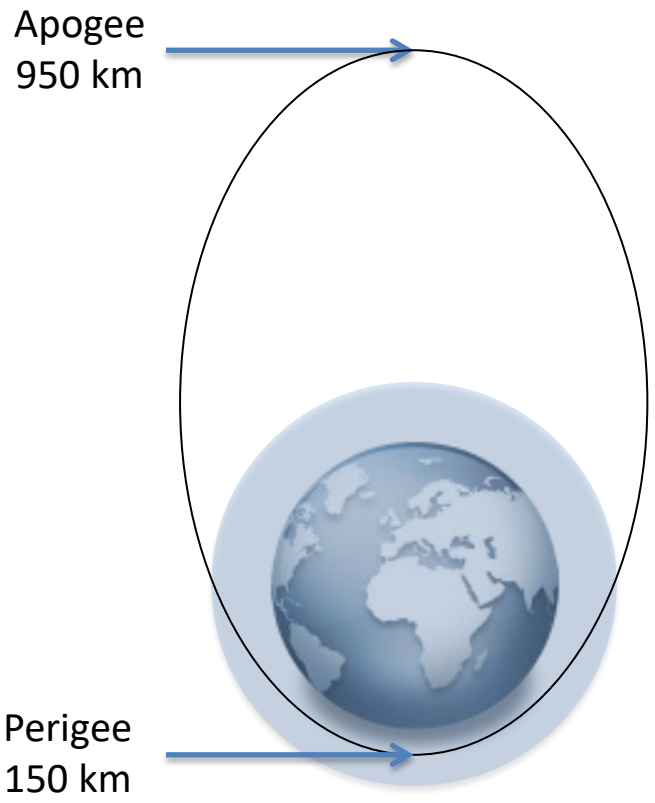
$A_{solar} \gg A_{scoop}$

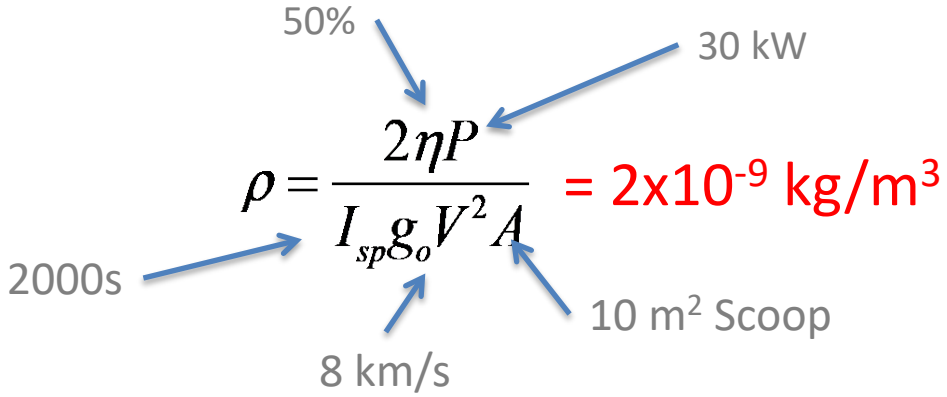
More Drag, More Power → More Drag, More Power

Elliptical Collection Orbit (ECO)

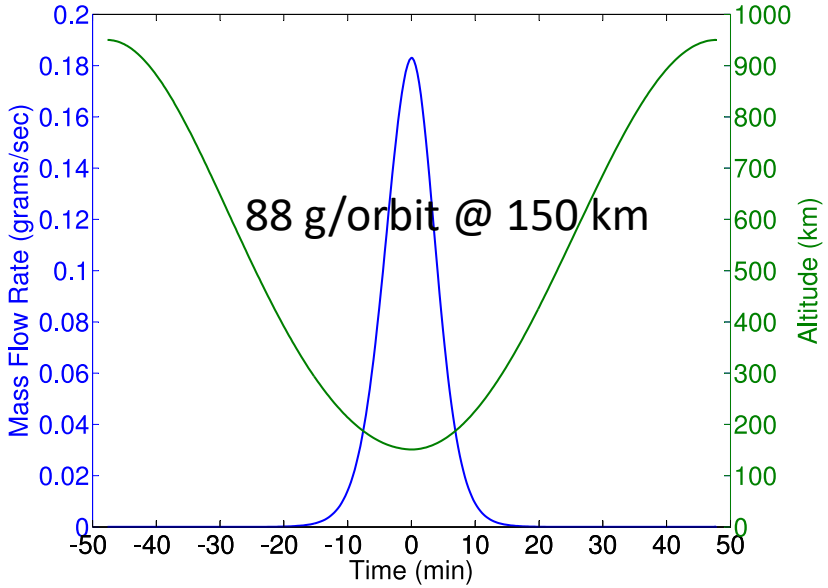
$$F_{drag} = \rho \cdot A \cdot V^2$$

$$T = 2\eta \cdot P/(Isp \cdot g)$$





Density of 1.9×10^{-9} kg/m^3



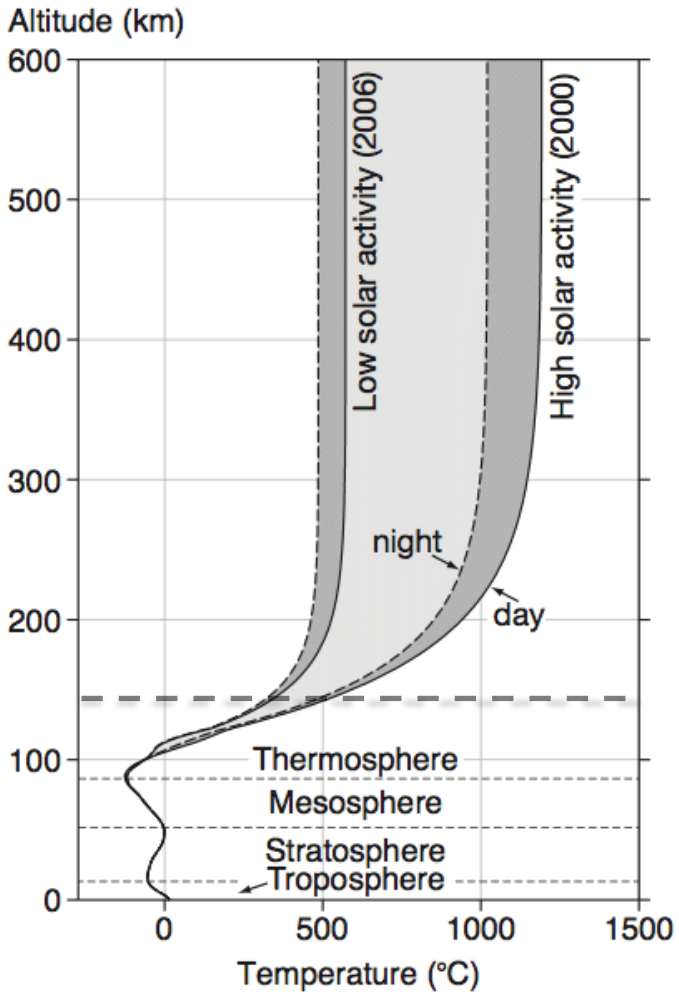
1. Reduced Solar Panels
2. Minimal draft make-up

Instantaneous altitude and mass flow rate for the lowest perigee orbit described earlier

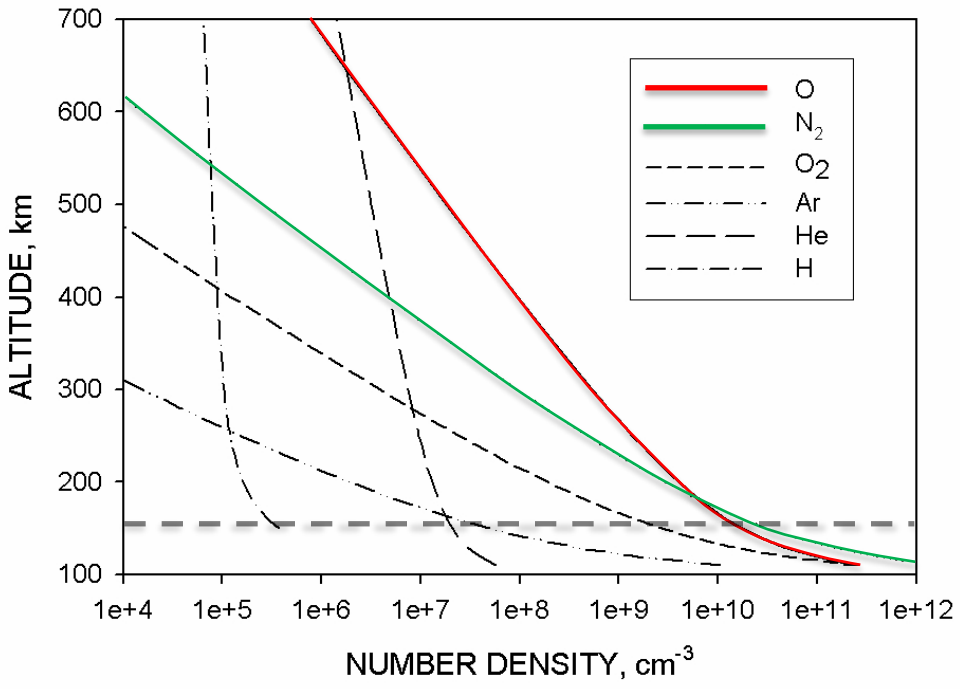
Atmospheric Conditions for RON

Target Perigee (150 km)

"Temperature" in the Thermosphere

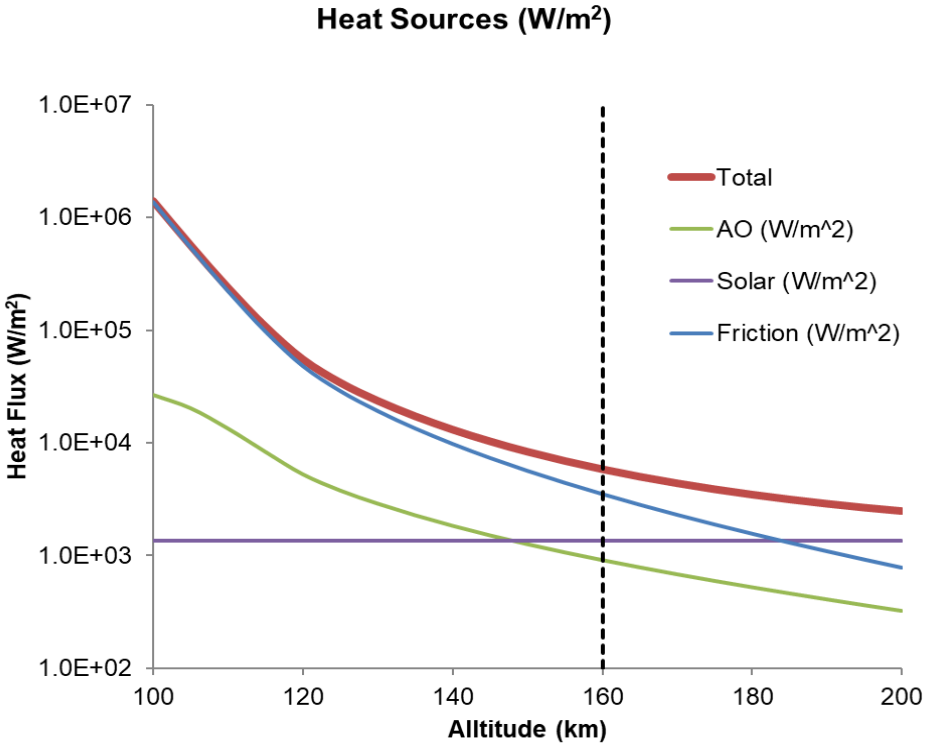


Density of atmospheric species as a function of altitude



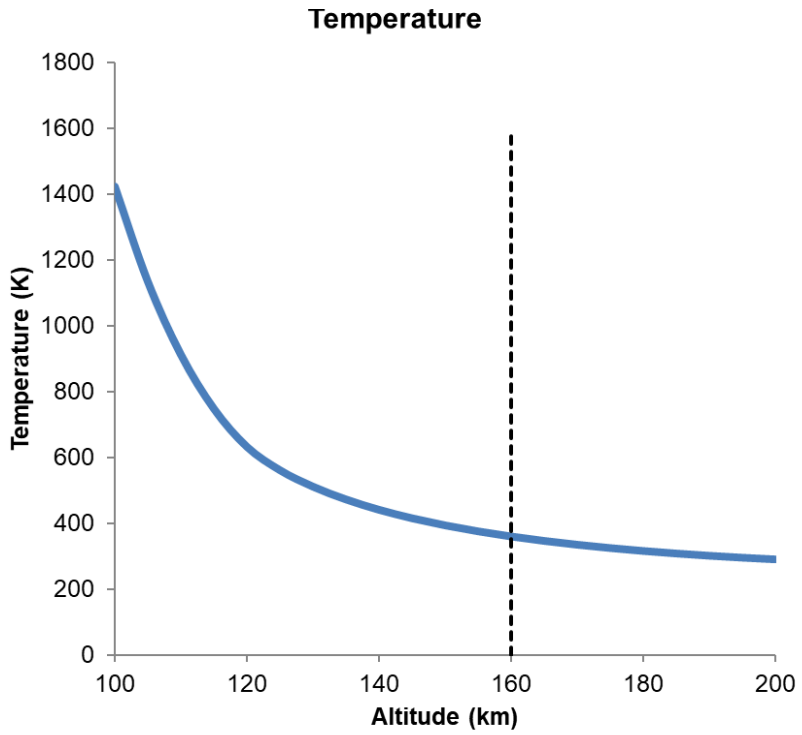
Scoop Collection System Thermal Analysis

Various sources of heat on the scoop as a function of altitude.



AO is the heat released from recombination of atomic oxygen. Flow stagnation (friction) is the largest contributor to scoop heating

Scoop temperature as a function of altitude

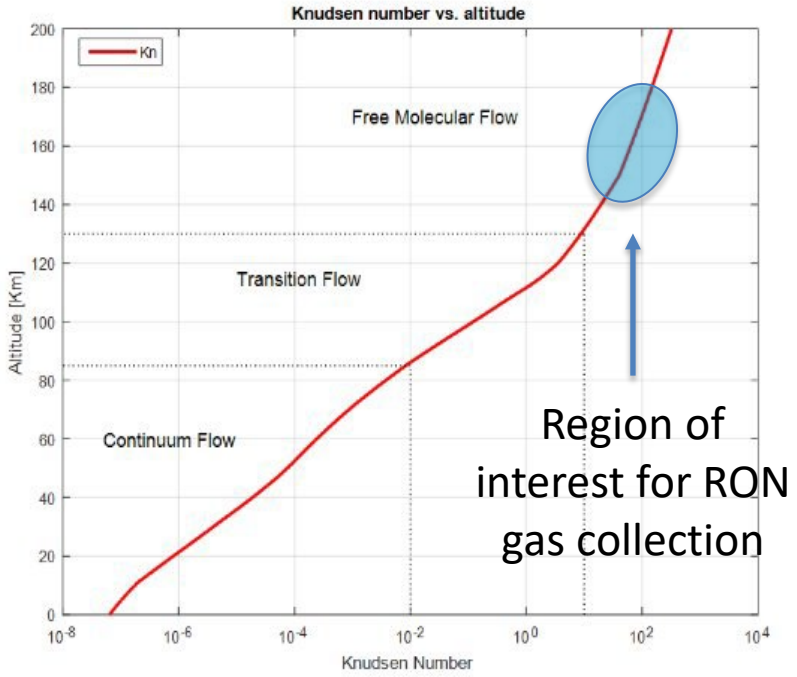


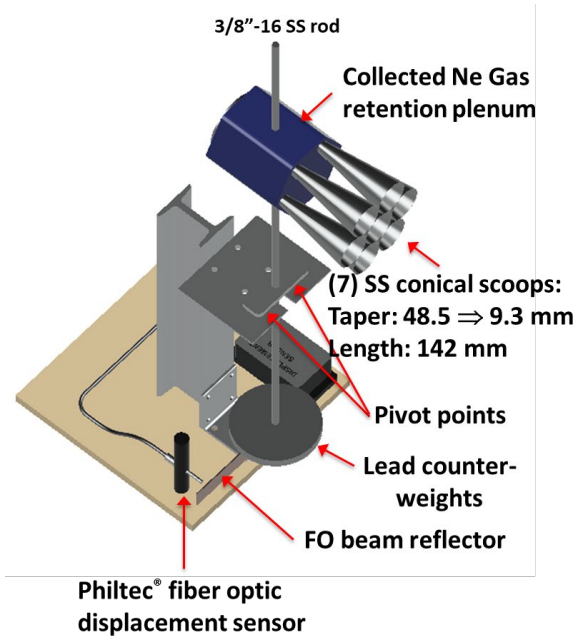
Radiation was the only loss channel considered in the calculation for cooling.

Knudsen Number vs. Altitude

Characteristic Length of 1 Meter

Spacecraft always remains in the molecular flow regime







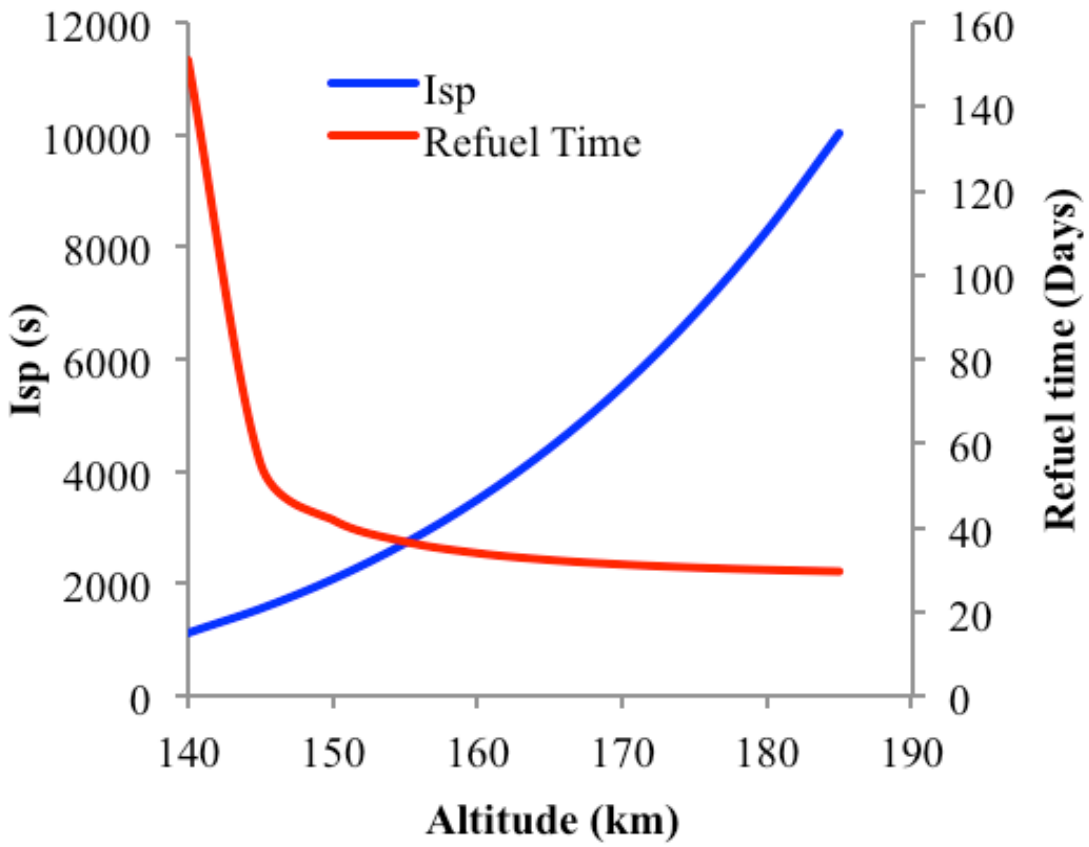
Worst-case estimate for drag:

$$F_{drag} = \rho \cdot A \cdot V^2$$

where ρ is the mass density of the atmosphere, A is scoop cross-sectional area, and V is the orbital velocity.

Experimental setup used to determine drag coefficient and scoop capture efficiency

Mission Space for:
10 m^2 Scoop with 30 kW EP Thruster

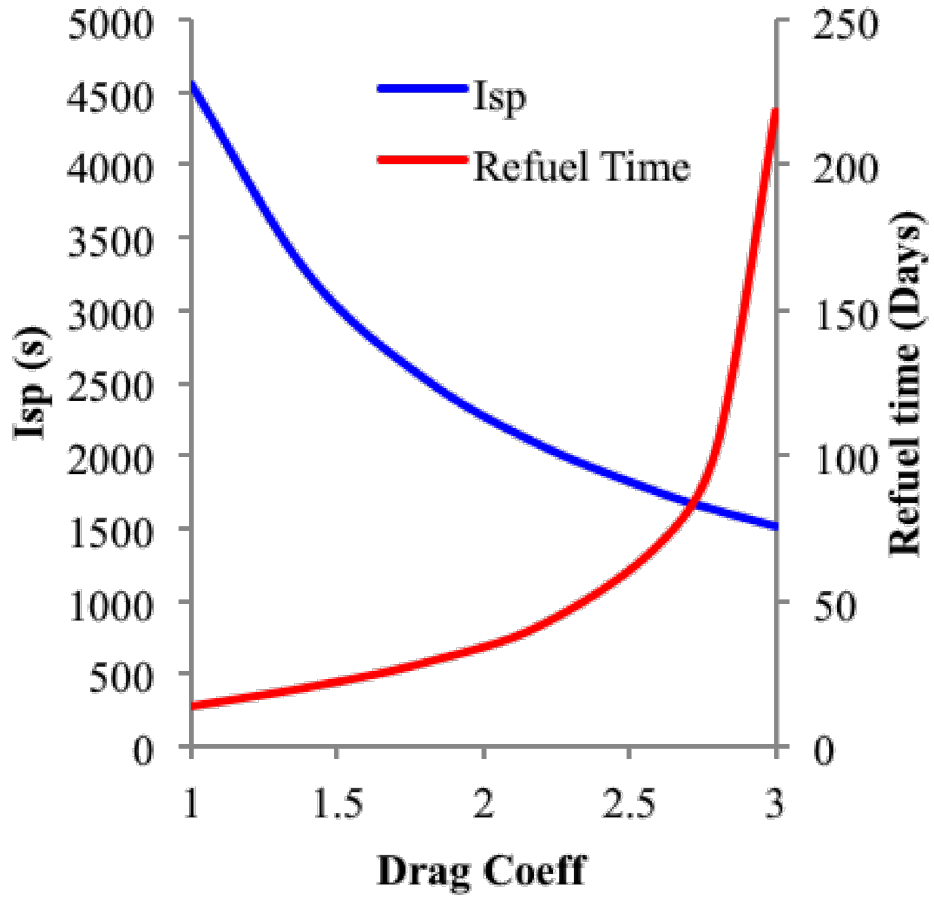


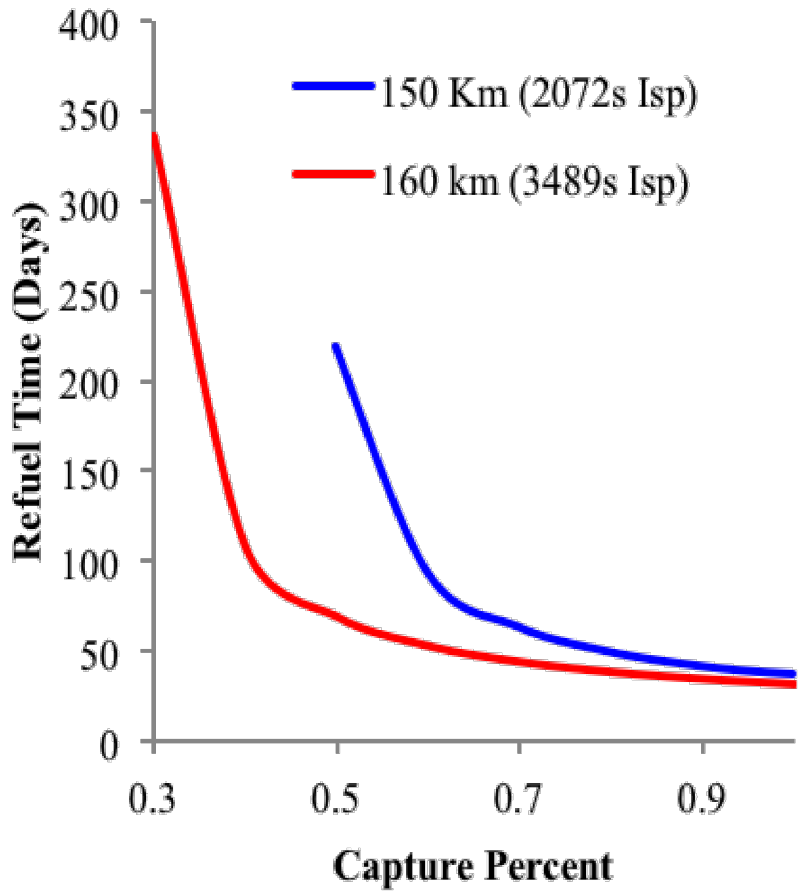
As altitude decreases

- Isp decreases
  ⇒ more thrust is needed at limited power
- Refuel time increases
  ⇒ more drag
  ⇒ more thrust
  ⇒ more propellant
  ⇒Less Isp
  More propellant

More Propellant need for Drag make, less can be stored, longer the refuel time

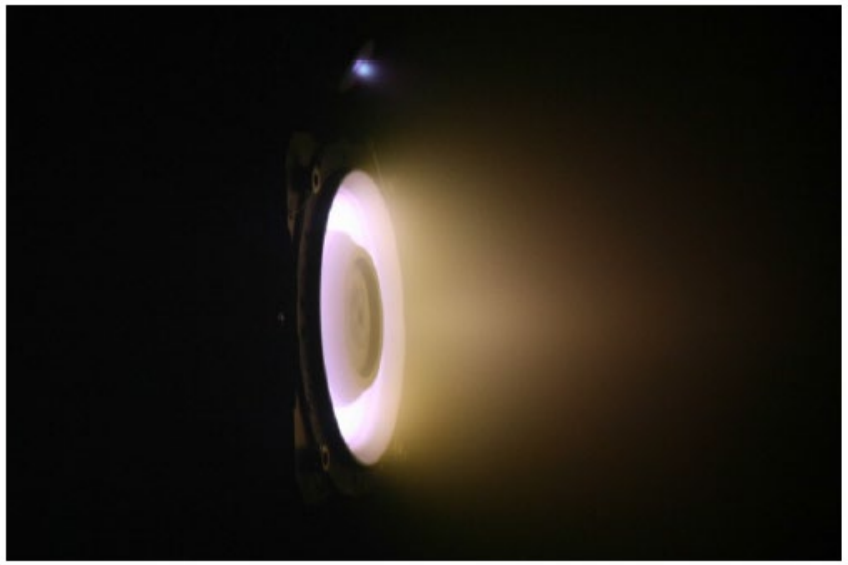
Critical Scoop Design Parameters



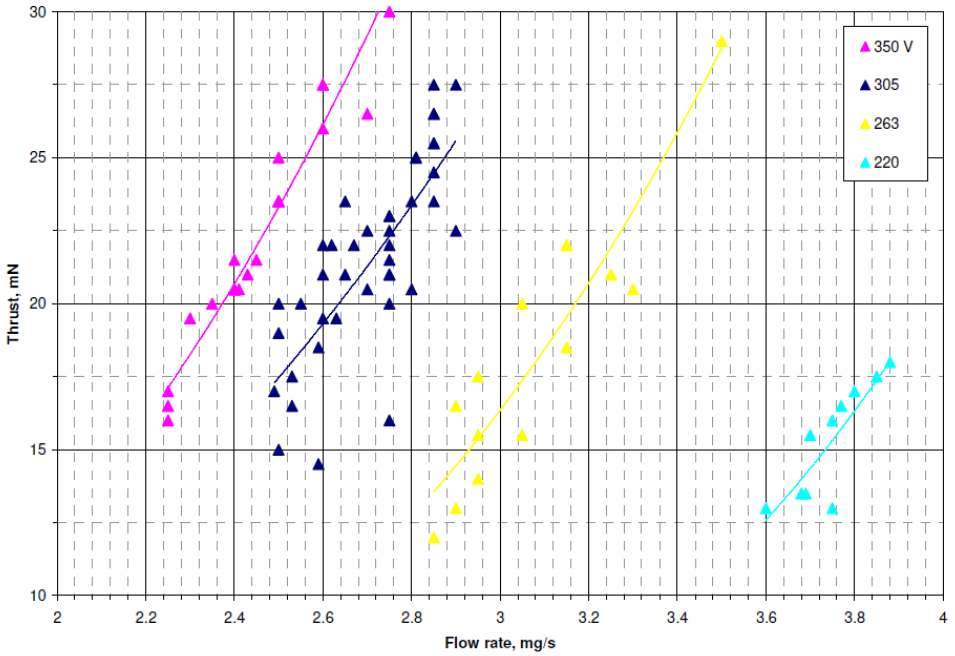


Hall Effect Thruster (HET) operation on a N_2-O_2 Mixture

- The thruster has operated stably during the 10 hours test.
- The measured thrust has been 30 mN at 1 kW
- At roughly half the efficiency of the Xenon results ⇒ Isp = 2000s.
- The thrust was a strong function of power

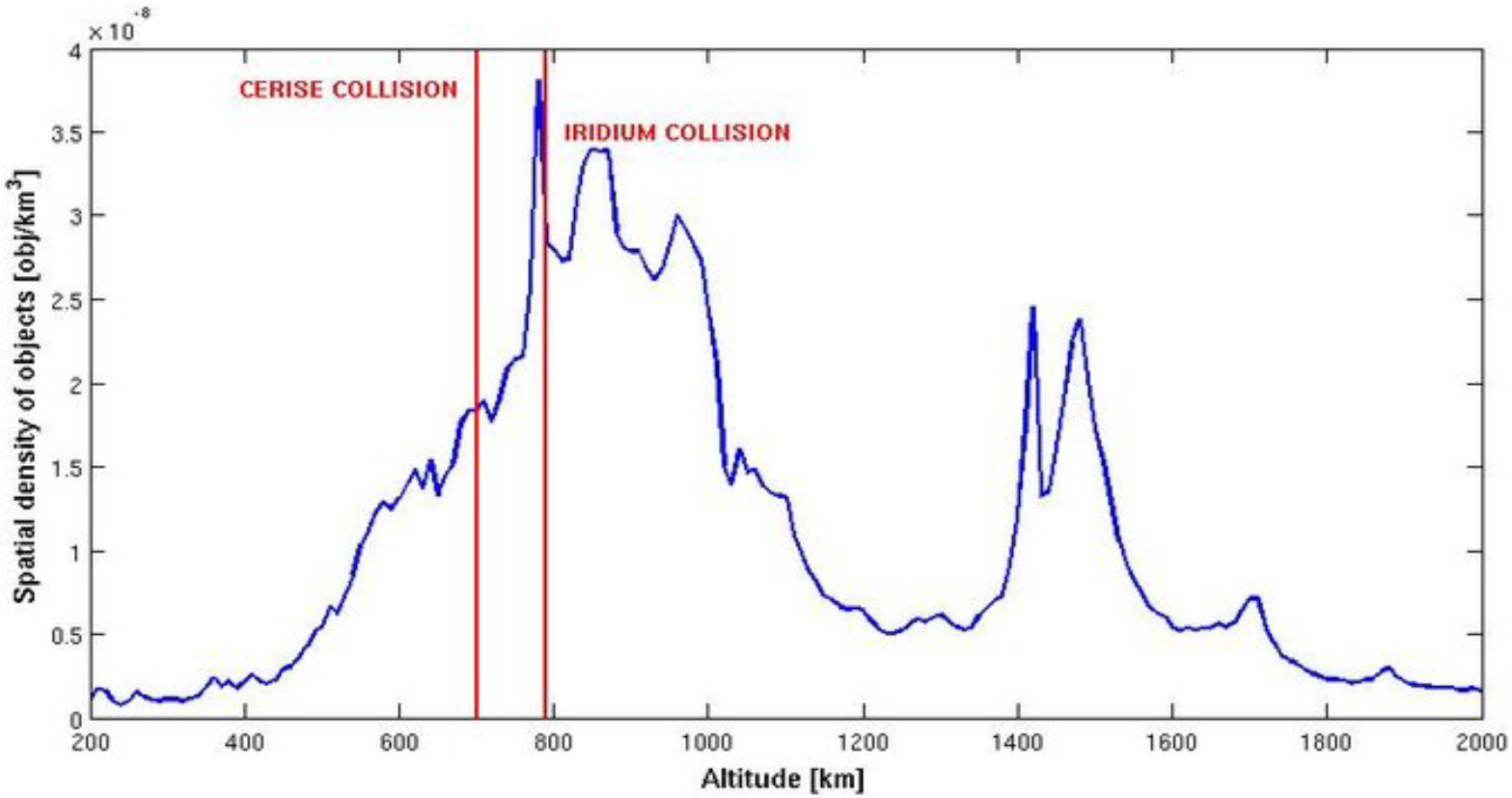


Thruster operating with N2-O2 mixture (305 V, 2.75 mg/s)



Thrust vs. flow rate with discharge voltage as parameter

The Orbital Debris Crises

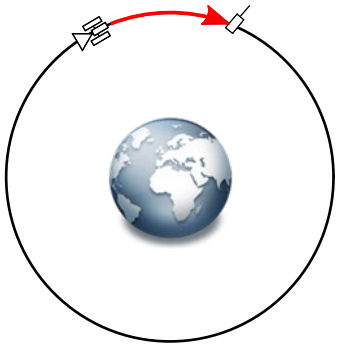


Orbital debris concentration by altitude

In 2009 the accidental collision between the Iridium 33 and Kosmos-2251 satellites created nearly 1500 kg of debris, resulting in a 30% increase in the collision probability to intact objects in low earth orbit

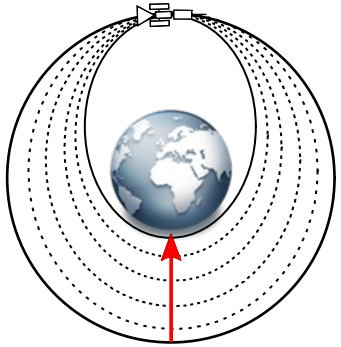
Sample Mission Architecture: ADR

The four mission stages of the RON system



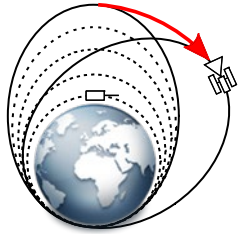
Rendezvous

From a matched obit, CHARON rendezvous with target debris (Target: 1MT satellite)



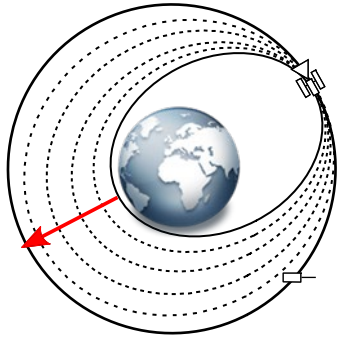
Walk-in

Using onboard propellant CHARON burns at apogee to ferry target to an Elliptical Collection Orbit (ECO)



Refuel & Reorient

Once in ECO, target will rapidly deorbit (~76 days), while CHARON refuels and reorients



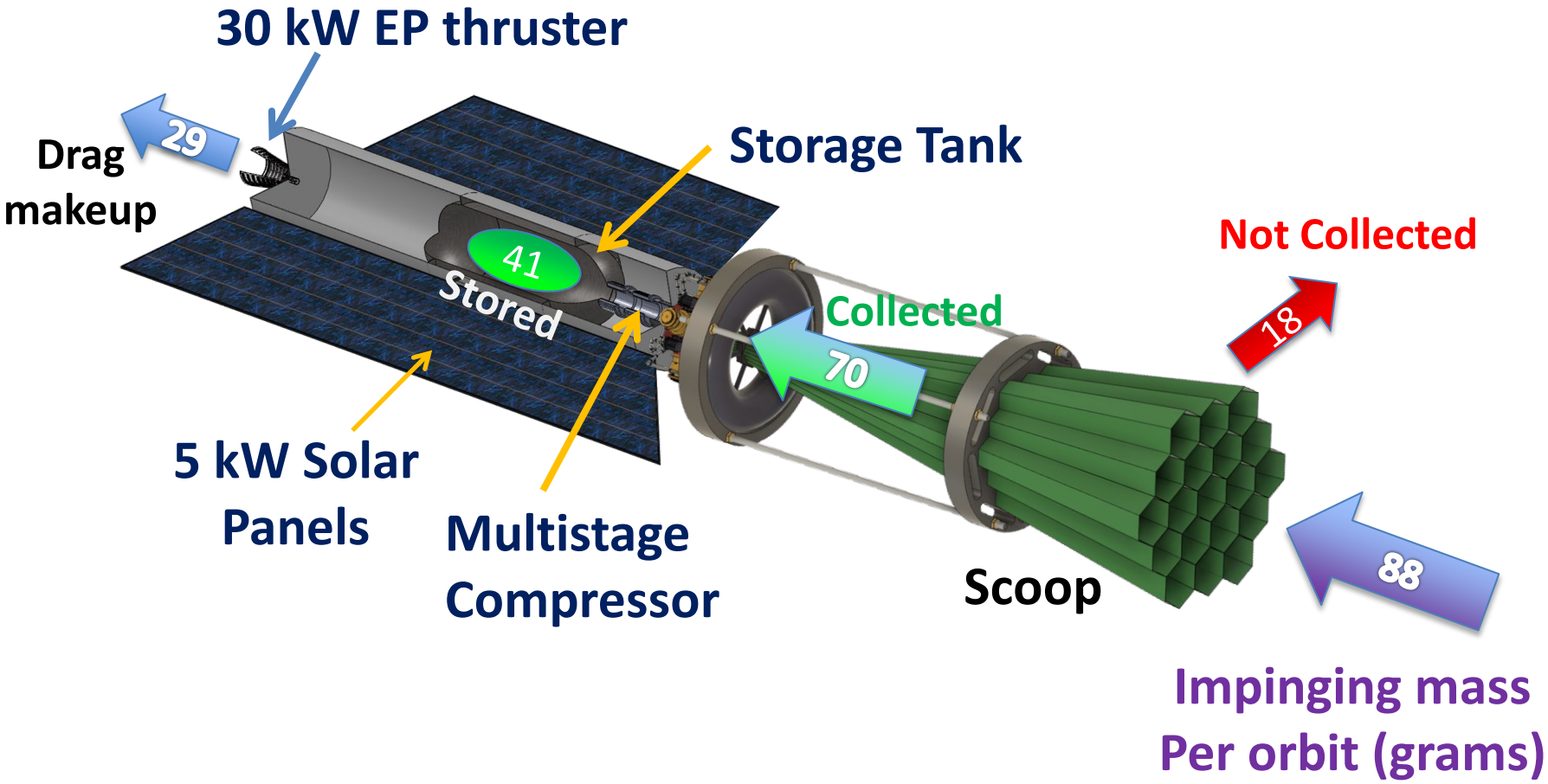
Walk-out

Once tank is full CHARON burns at apogee back to a circular orbit of next target

Stage Characteristics

Stage	Operation	Propellant requirement (kg)	Time, hrs (days)	Delta-V (m/s)
1	Rendezvous	1.82	24 (1.00)	117
2	Walk in	14.80	222 (9.26)	223
3	Refuel & Realign	NA	771 (32.13)	N/A
4	Walk out	3.41	51 (2.14)	223
	TOTAL	**20.03**	**1069 (44.53)**	**563**

Prototype Design for RON Based on Experimental Results and Mission Analysis

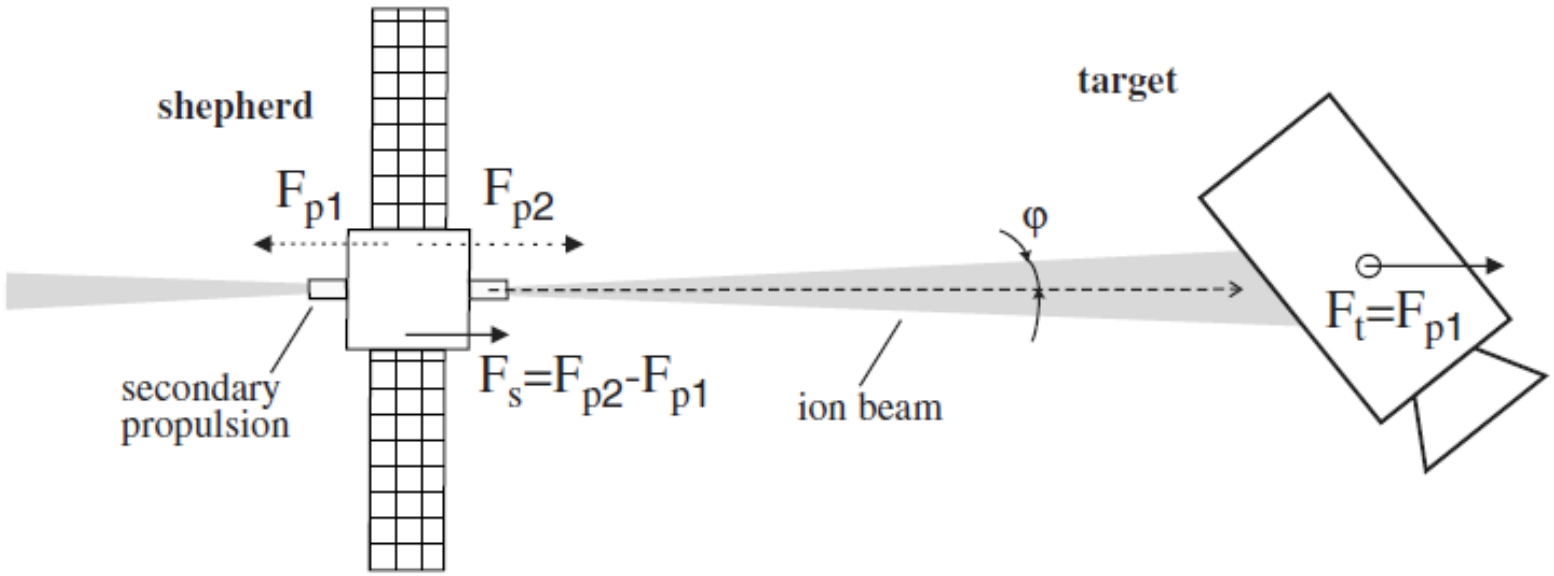


Schematic of RON propellant collection and usage during elliptical orbit. Drag makeup assumes a drag coefficient of 2. A collection efficiency of 80% during perigee is also assumed. Orbital perigee is at 150 km.

Mass Budget for Full-scale RON

Component	Mass (kg)	Description	TRL
Tank	20	50 kg propellant at 1000 psi, carbon overwrapped titanium alloy tank	5
Scoop	60	Conical silica scoop with 2 mm walls and a 3.5 m diameter	3
Compressor	60	Multi-stage compressor system	3
Thruster	130	30 kW HET thruster	4
ADCS	10	2 gyroscopes and 8 thrusters	8
Comm. and Data	15	Antenna, diplexer, receiver, transmitter, and encoder	8
Power	35	Power conditioning unit	8
Batteries	55	36.8 MJ lithium polymer batteries (900 kJ/kg)	8
Solar arrays	15	XTJ triple junction cells of 84 mg/cm^2 and array area of 13.66 m^2	6
Instruments	30	Star tracker, earth sensor, LIDAR unit, and telescopic camera	8
Capture Hardware	20	Estimate	2
Structure	60	Estimate	N/A
Thermal	10	Estimate	N/A
Dry Mass	520		
Margin	130	25% of dry mass	
Propellant	50		
Total Mass	700		

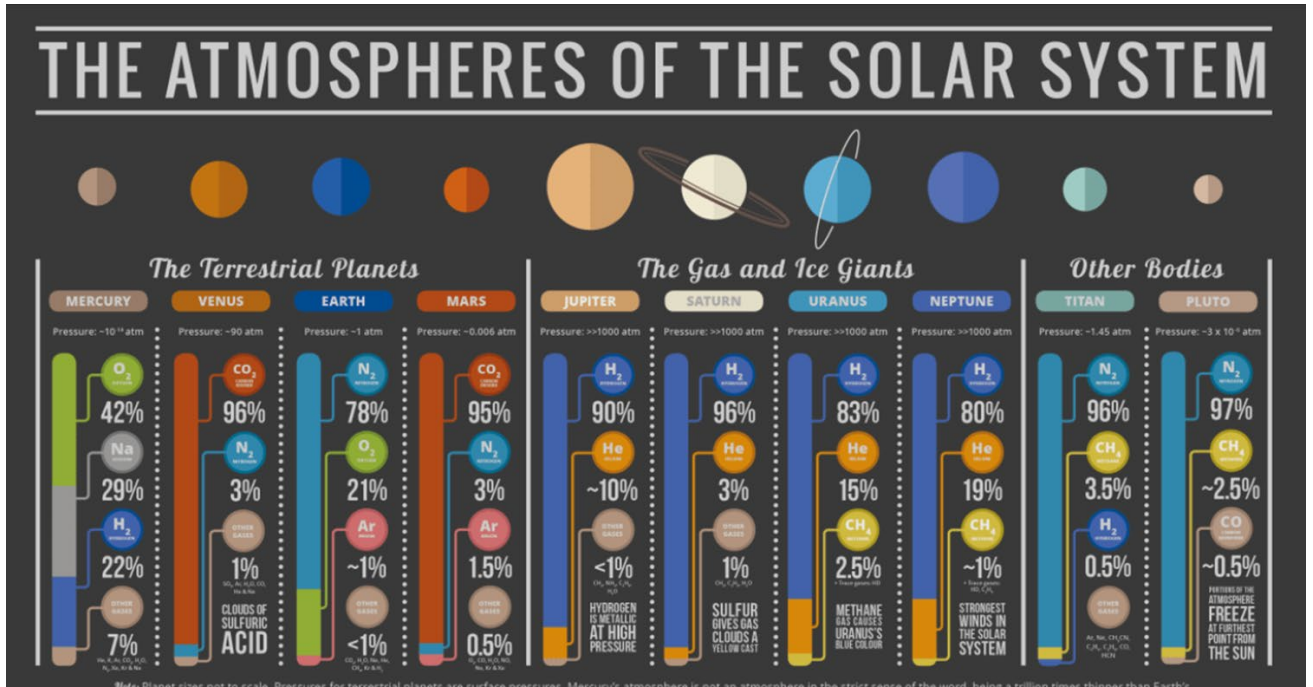
Schematic of the Ion Beam Shepard (IBS) satellite for deorbiting space debris



RON for Exploration and Resource Utilization on Other Planetary Bodies

Candidate planetary and atmospheric data for a REfuelable Planetary Orbiter (REPO) mission.

Planet	Radius (10^6 m)	Mass (10^24 kg)	Orbital Velocity (m/s)	Orbital Period (hr.)	Height where ρ ~ 1e-9 kg/m^3 (km)	Principal Gases (%)
Earth	6.38	5.97	7,900	1.4	170	N2 [78] O2 [21] Ar [1]
Mars	3.4	0.642	3,549	1.7	135	CO2 [95] N2 [3] Ar [1]
Venus	6.05	4.87	7,327	1.4	135	CO2 [96] N2 [3]
Jupiter	71.5	1898	42,078	3.0	550	H2 [90] He [10]
Saturn	60.3	568	25,066	4.2	950	H2 [96] He [3]
Uranus	20.6	86.8	16,764	2.1	800	H2 [83] He [15] CH4 [2.5]
Neptune	24.8	102	16,563	2.6	810	H2 [80] He [19] CH4 [1]
Titan	2.57	0.134	1,865	2.4	900	N2 [96] CH4 [3.5] H2 [0.5]



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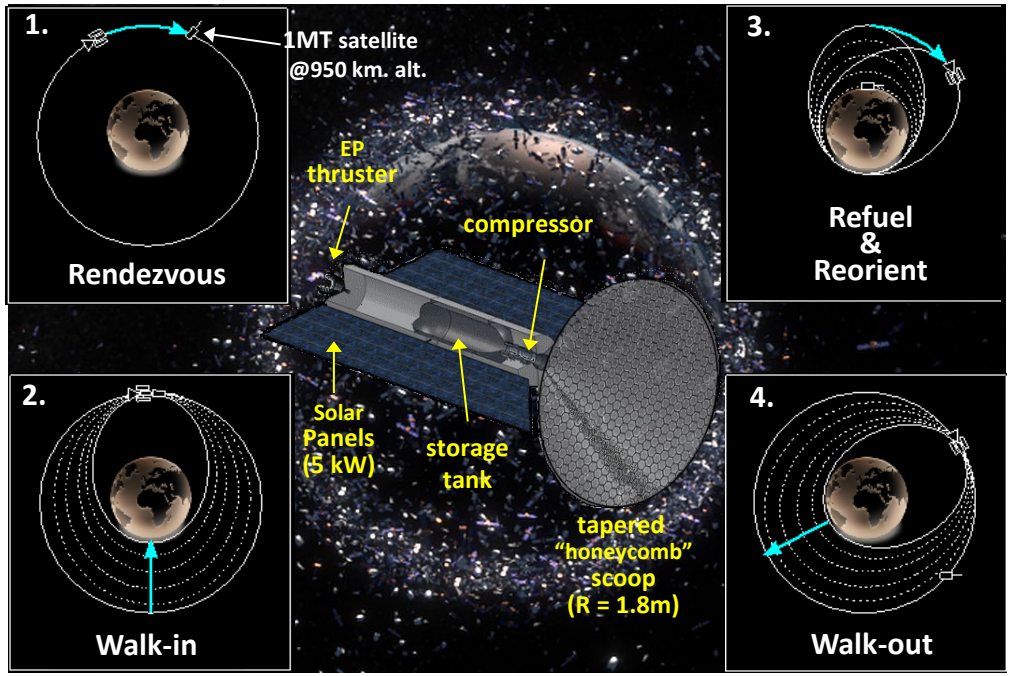
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