Entry, Decent and Landing of an Amphibious Quadcopter Swarm for the Exploration of Titan

Adarsh Rajguru[1,2]
Brian Franz[1,2]
Addison Faler[1]

[1] Ph.D Candidate, *University of Southern California, Department of Astronautical Engineering 854B Downey Way, Los Angeles, CA 90089 US*

[2]*IPPW Student Travel Scholarship*

Overview

1) Mission Architecture

   → Goals

   → Science Objectives

2) EDL

   → Methodology

   → Hypersonic Entry

   → Supersonic Descent

   → Subsonic Landing and Payload

Mission Goals

- Safe deployment of a quadcopter swarm (1 mother and 5 daughters) through Titan's atmosphere
- Insertion of swarm over / onto Titan's Kraken Mare (landing ellipse of 400 x 800 km) or Ligeia Mare (landing ellipse of 420 x 350 km).
- Mission duration to achieve primary science objectives should not exceed more than 11 years.

Science Objectives, Investigations and Instrumentation - 1

Objective	Investigation	Instrumentation
Characterize amount of liquid on Titan surface	**Determine depth of sea at landing site**	**Echo Sounder**
	Determine surface area of the sea	**Descent Cameras and DISR (Descent Imager / Spectral Radiometer)**
	Quantify the total major organic inventory present in the lakes and seas	**FTIR Spectrometer, Turbidimeter, Sea Properties Package (SPP) and Hi-Res GC-GC MS (High Resolution Gas Chromatography Mass Spectrometer)**

Blue - instrumentation not onboard quadcopter mission

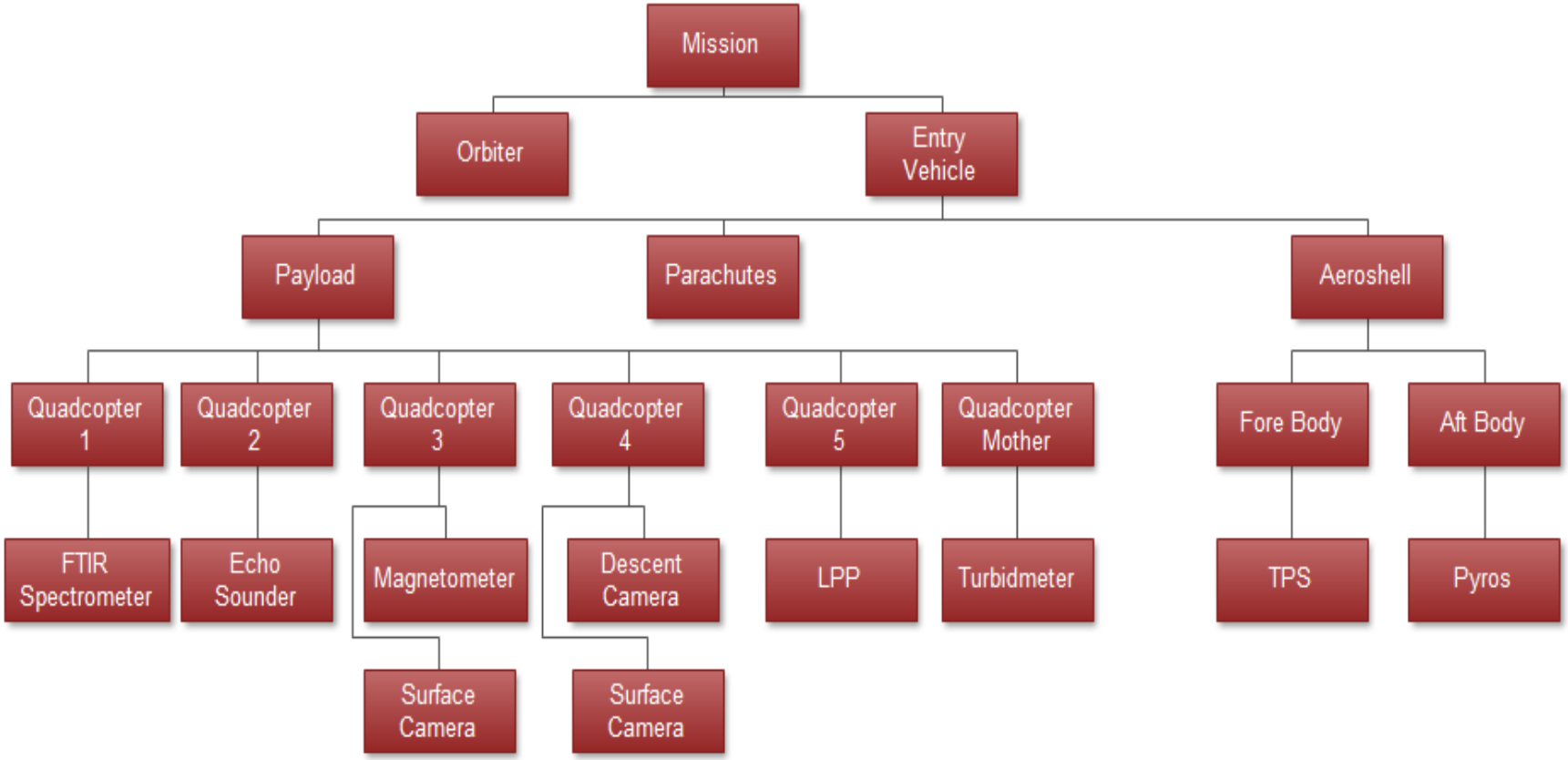
Ref: J. Hunter Waite, *Mission Concept Study: Planetary Science Decadal Survey JPL Team*
X Titan Sea Probe Study Final Report, April 2010

Science Objectives, Investigations and Instrumentation - 2

Objective	Investigation	Instrumentation
Characterize major processes transforming the surface throughout time	Characterize origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events	Descent Cameras and DISR (Descent Imager / Spectral Radiometer)
Determine existence of subsurface liquid water ocean and whether Titan has an intrinsic magnetic field	Determine depth of the sea at the landing site over Titan's 16-day orbit	Echo Sounder, Turbidimeter and Sea Properties Package (SPP)
	Determine the included magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	Magnetometer

Blue - instrumentation not onboard quadcopter mission
Red – fully completed/accomplished science objective from Decadal Survey

EDL Systems Engineering Tree



Methodology - Monte Carlo Simulation

Monte Carlo Simulation

>> Total number of simulations or permutations and combinations 100,000

>> Defined boundary conditions for optimization operation on MATLAB

Optimization boundary conditions obtained from the Monte Carlo Simulation

>> Entry Velocity (4.5 – 13 km/s)

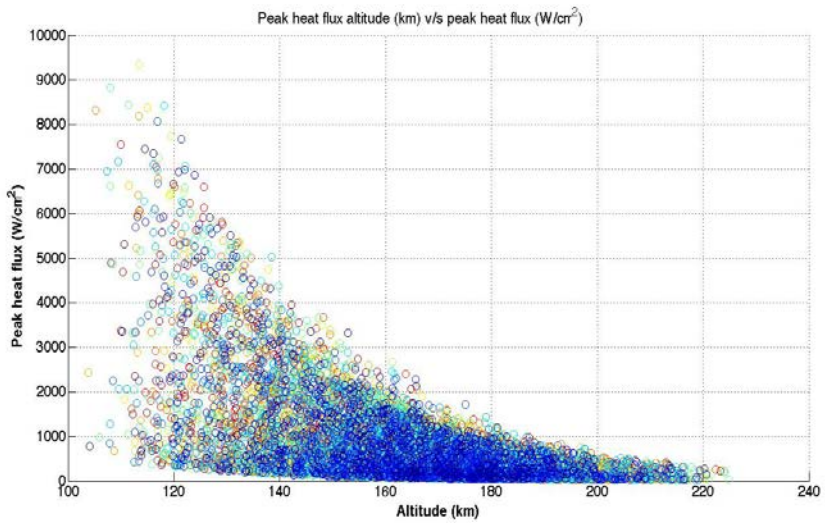
>> Entry Altitude (80 – 200 km)

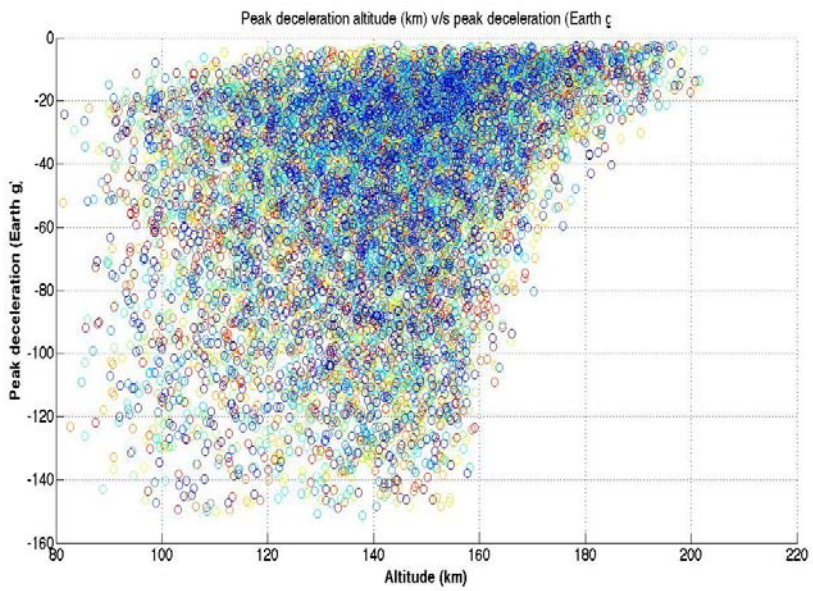
>> Diameter of the heat shield (0.5 – 1.5 meters)

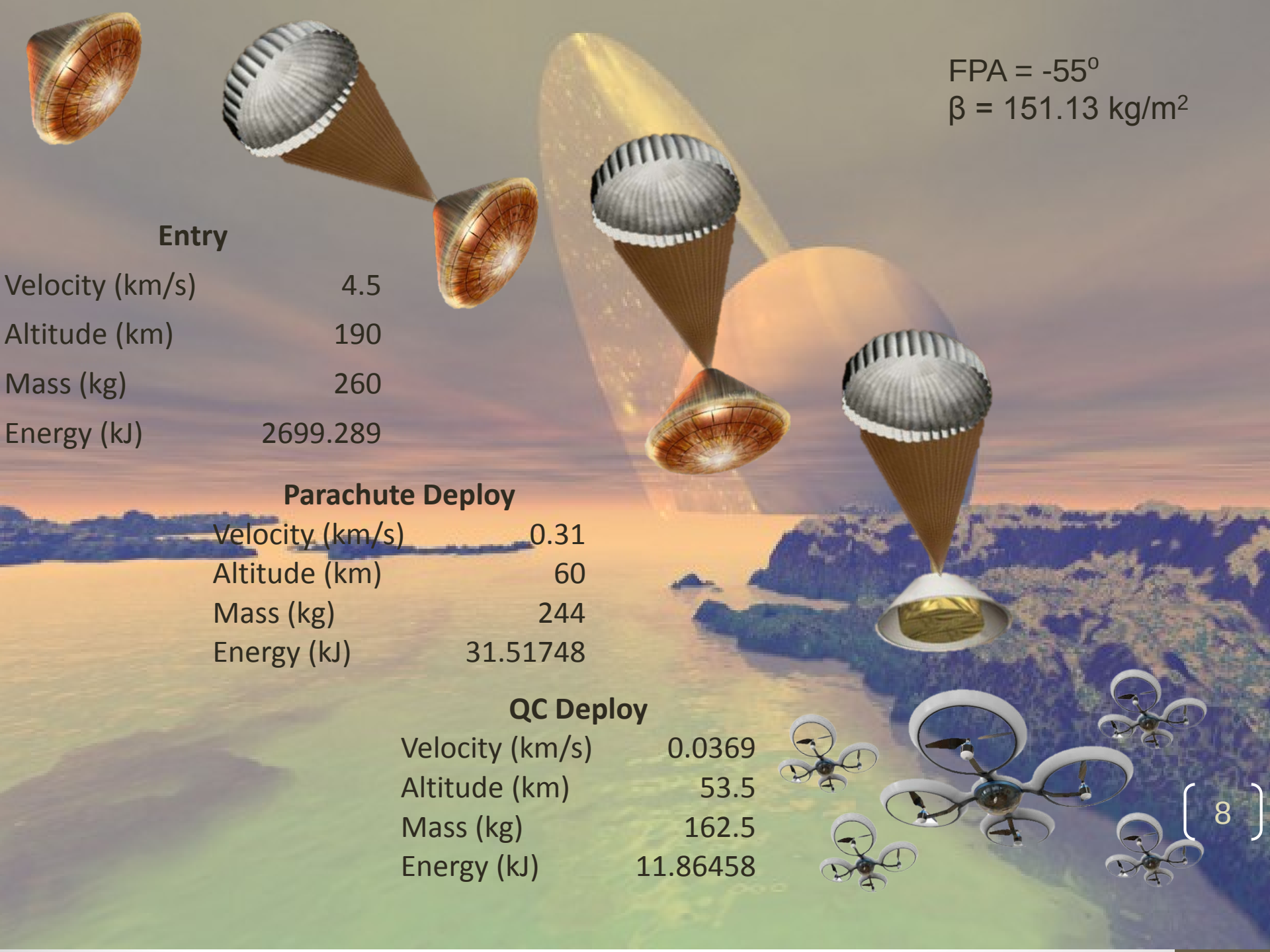
>> Flight Path Angle (-80^0 <-> -6^0)

>> Parachute Diameter (2 – 4 meters)

>> Sphere Cone Angle (30° – 70°)







FPA = -55°
β = 151.13 kg/m²

Entry

Velocity (km/s)	4.5
Altitude (km)	190
Mass (kg)	260
Energy (kJ)	2699.289

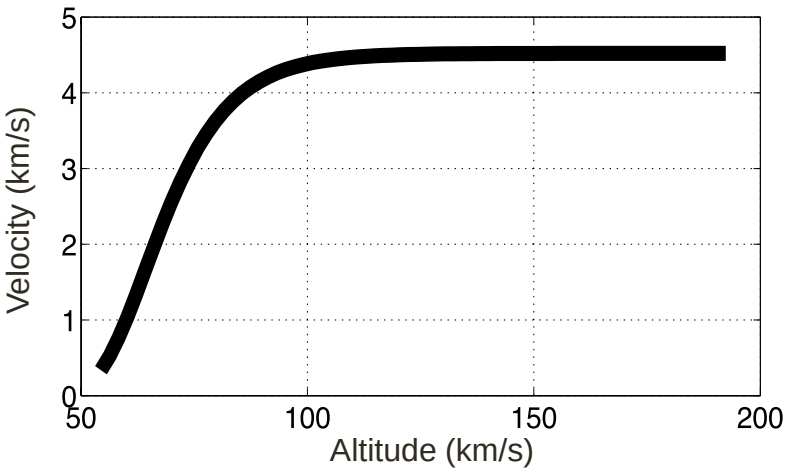
Parachute Deploy

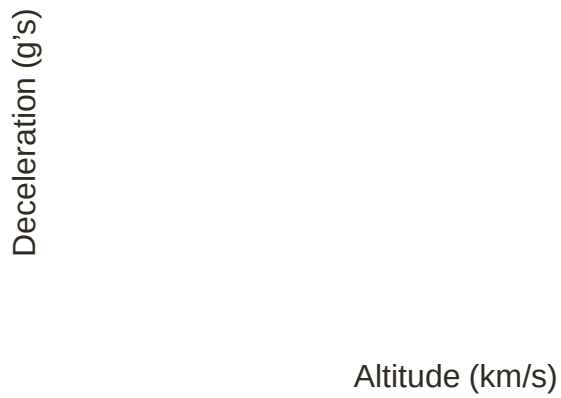
Velocity (km/s)	0.31
Altitude (km)	60
Mass (kg)	244
Energy (kJ)	31.51748

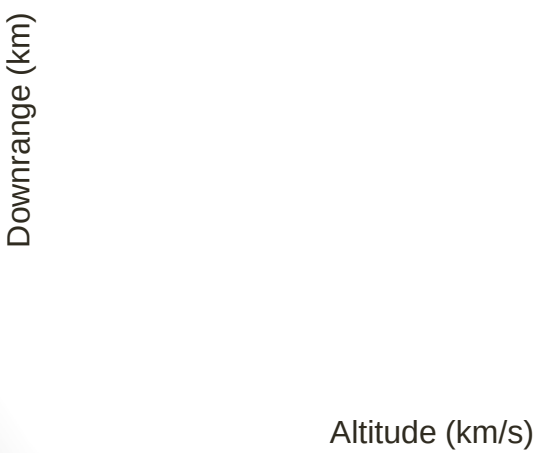
QC Deploy

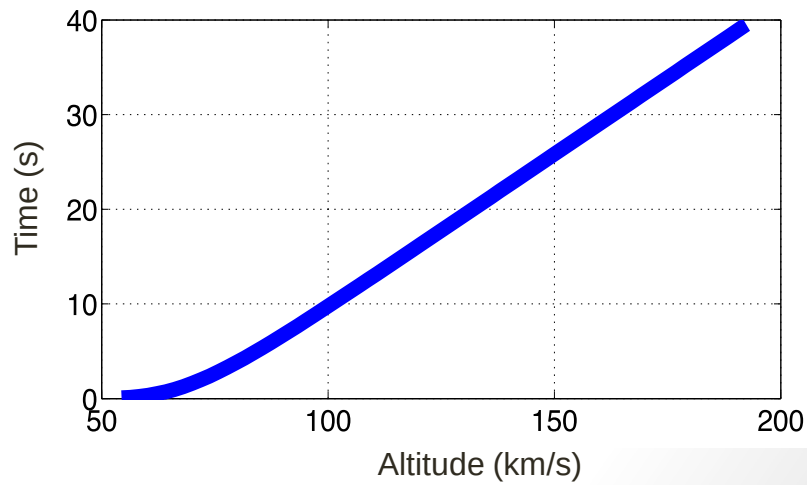
Velocity (km/s)	0.0369
Altitude (km)	53.5
Mass (kg)	162.5
Energy (kJ)	11.86458

Hypersonic Trajectory

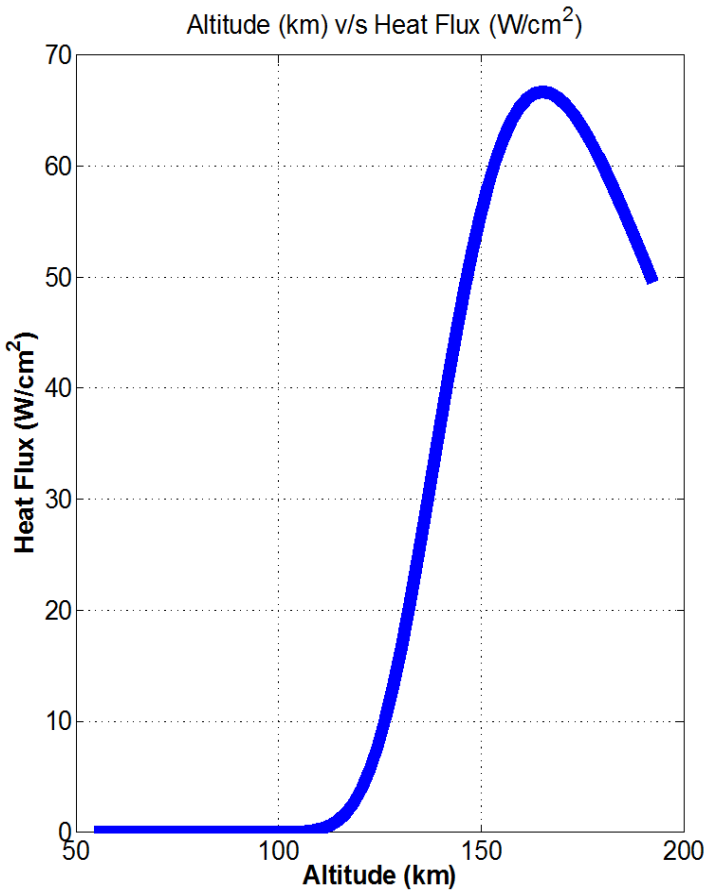


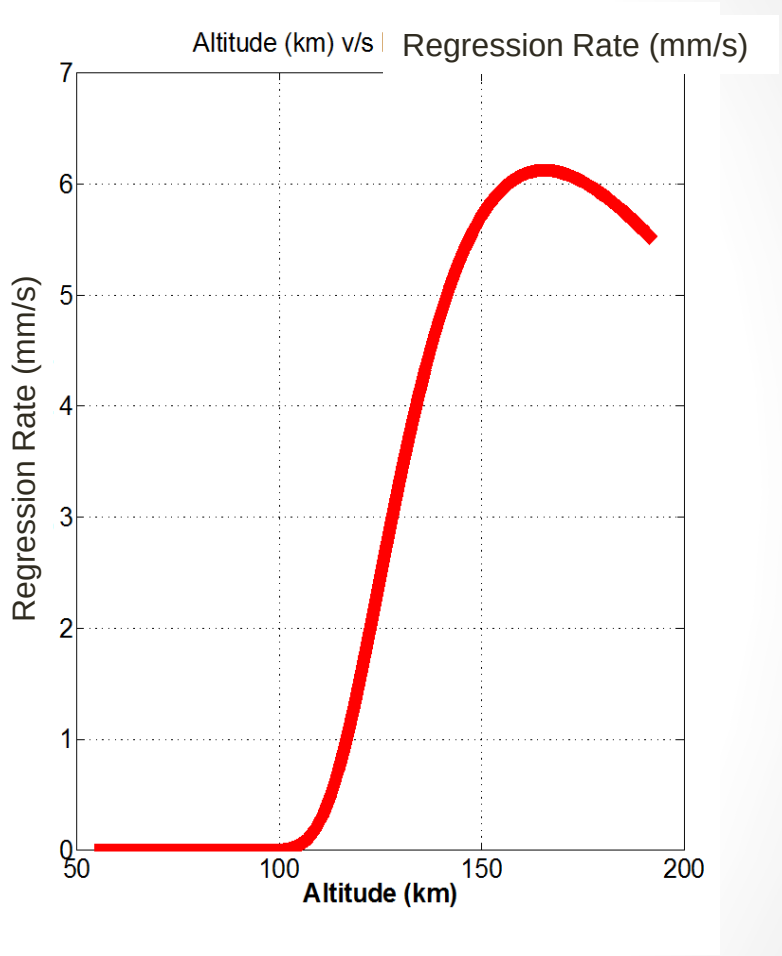






Hypersonic Heating



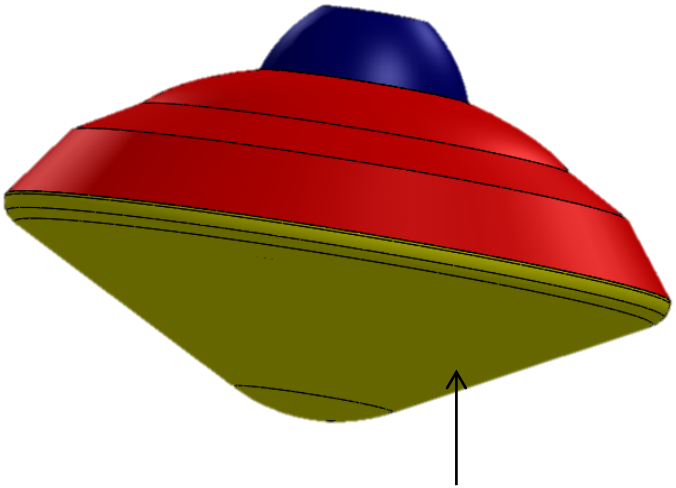


Peak Heat Flux = 66 W/cm^2

Total thickness regressed = 4 cm

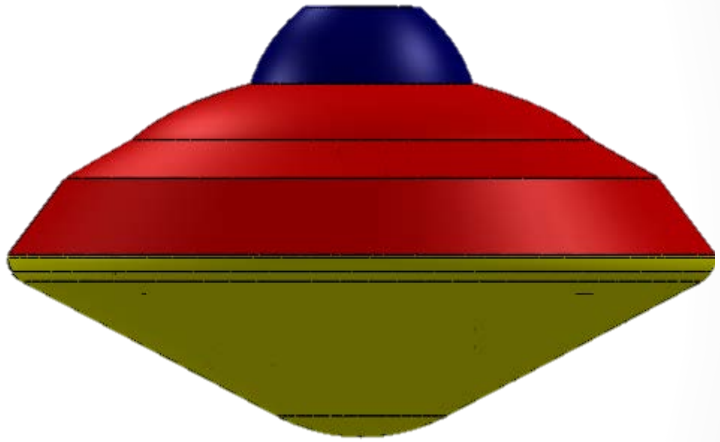
Total Heat Load = 9.585 MW

Heat Shield Size and Selection



SCA= 63.8˚
Thickness= 6 cm

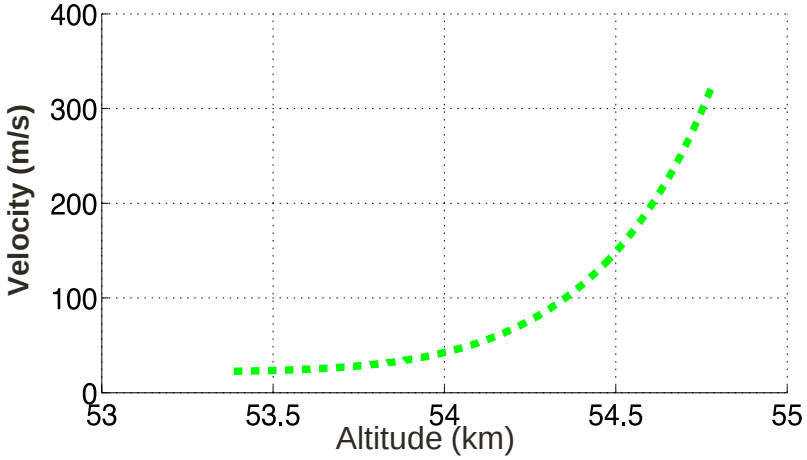
Material: PICA
ρ=265 kg/m^3
ε=0.85
Heritage: Hayabusa

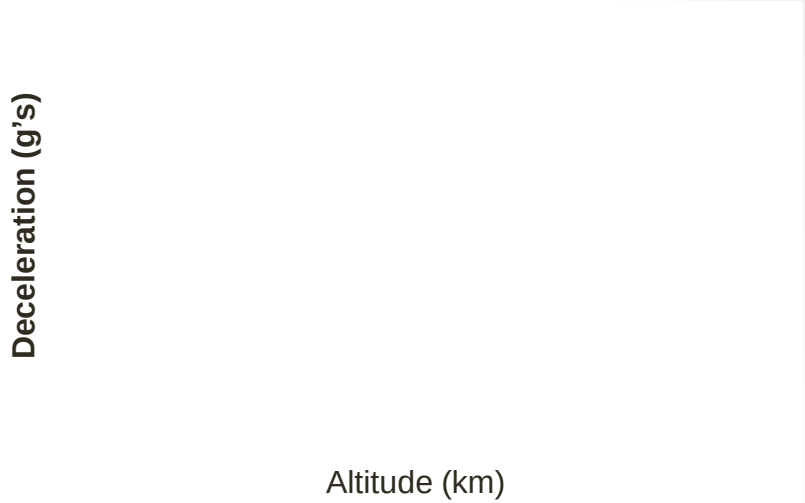


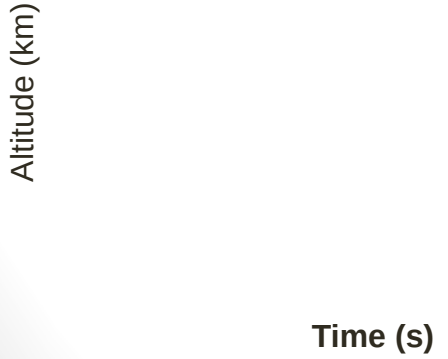
|----------D=1.48 m----------|

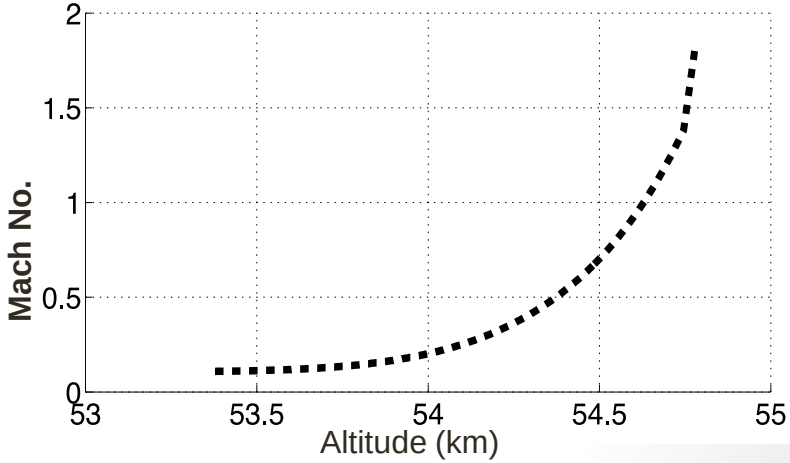
Ref: Toshiyuki Suzuki and Kazuhisa Fujita, *Post flight Thermal Protection System Analysis of Hayabusa Reentry Capsule* , JOURNAL OF SPACECRAFT AND ROCKETS, Vol. 51, No. 1, January – February 2014

Supersonic Trajectory





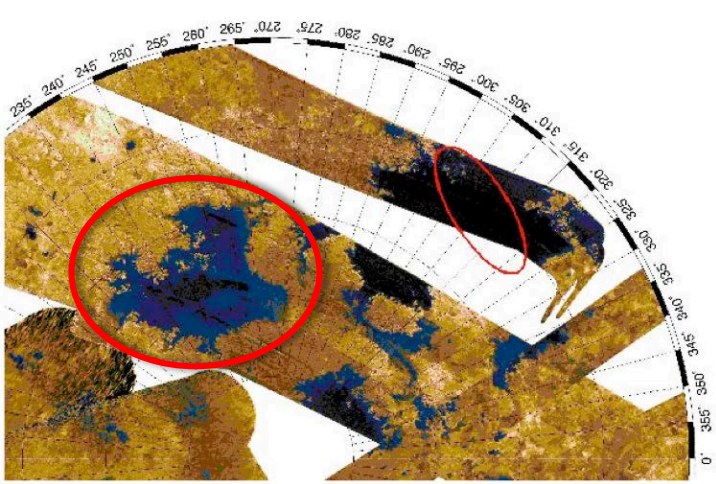




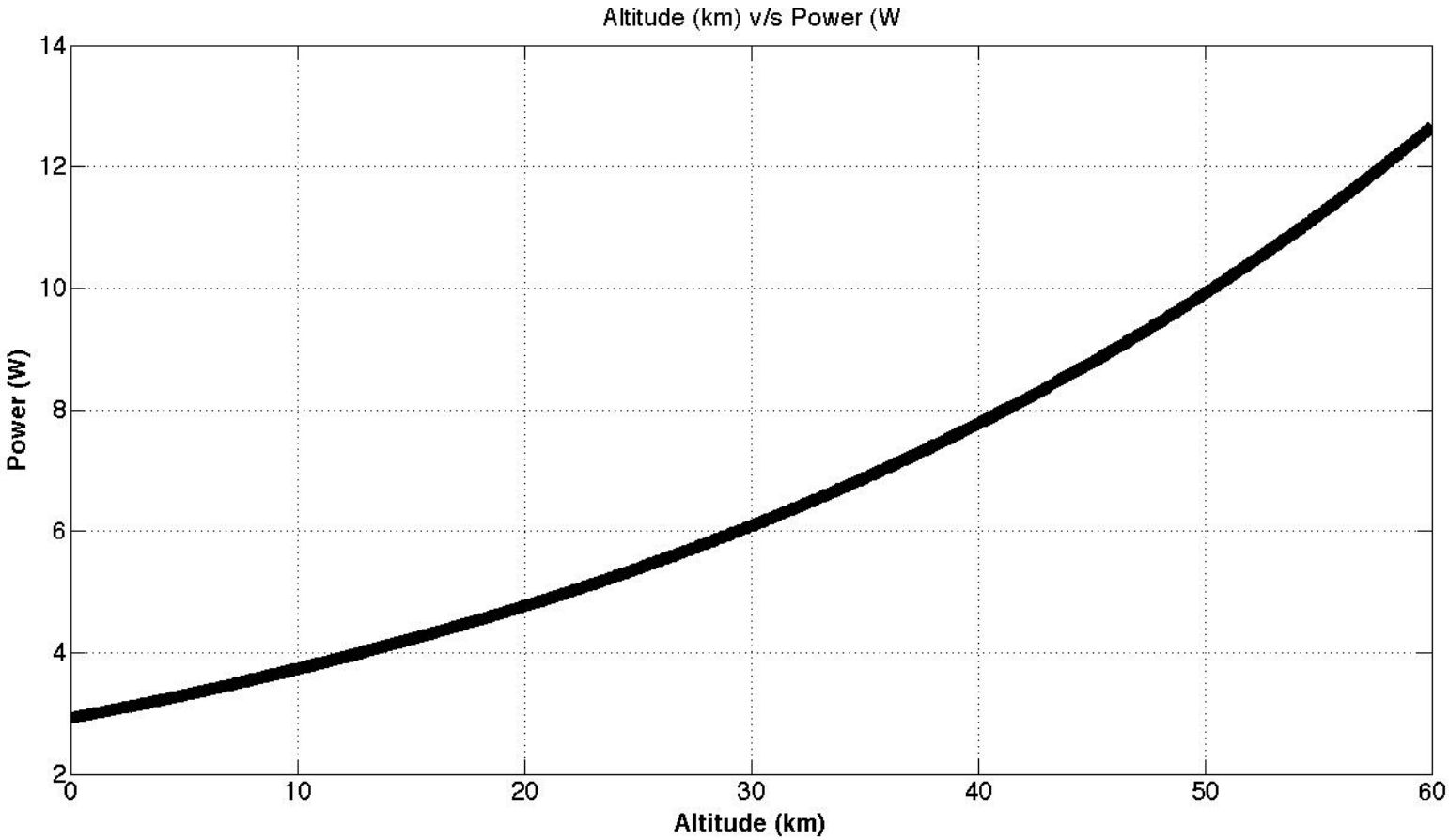
Supersonic Parachute Selection

Parachute			
Type	**Heritage**	**Opening Load Factor**	**Diameter (m)**
DGB	Viking	1.1	2.2

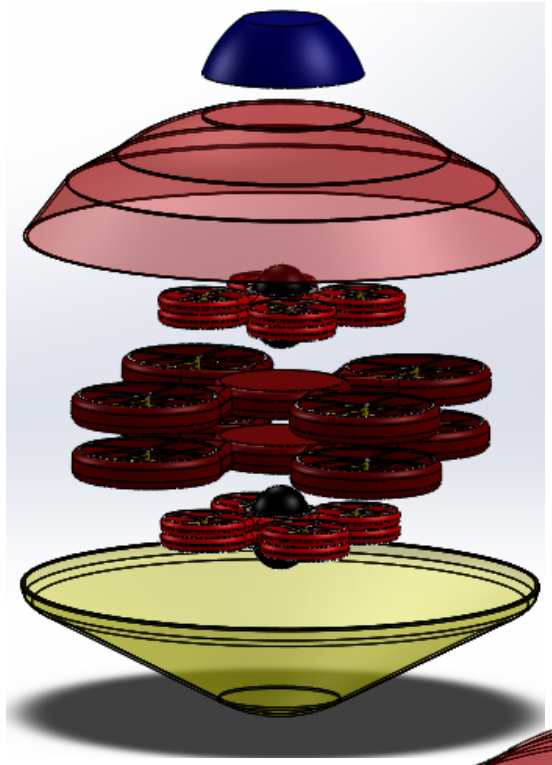
Supersonic Descent Parameters			
Deployment Mach #	**Altitude @ Deployment (km)**	**Terminal Velocity (m/s)**	**Peak Load (N)**
1.8	55	36.9	6827



Subsonic Landing

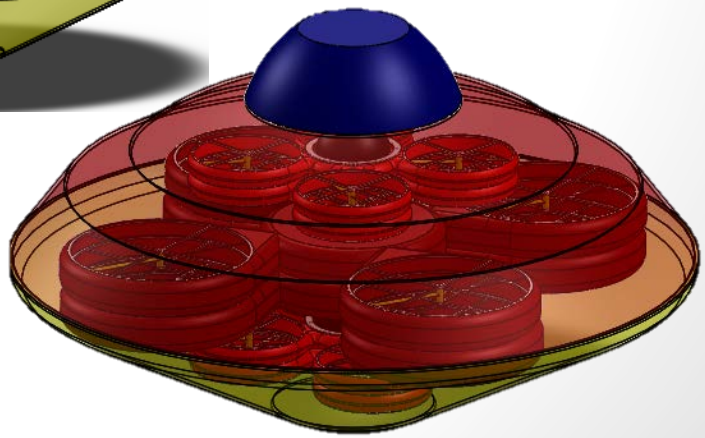


Payload Packing



Daughter quadcopter payload limit: ~1 kg

Mother/larger daughter quadcopter payload limit: ~4 kg



Summary

EDL Focus

→ Methodology – Monte Carlo Style Simulation based upon 6 specified inputs

- v_e, h_e, D_{HS}, FPA, θ, D_P

→ Hypersonic Entry – Trajectory and Heating Results from optimized input set

→ Supersonic Descent – Trajectory and Parachute Selection

→ Subsonic Landing and Payload

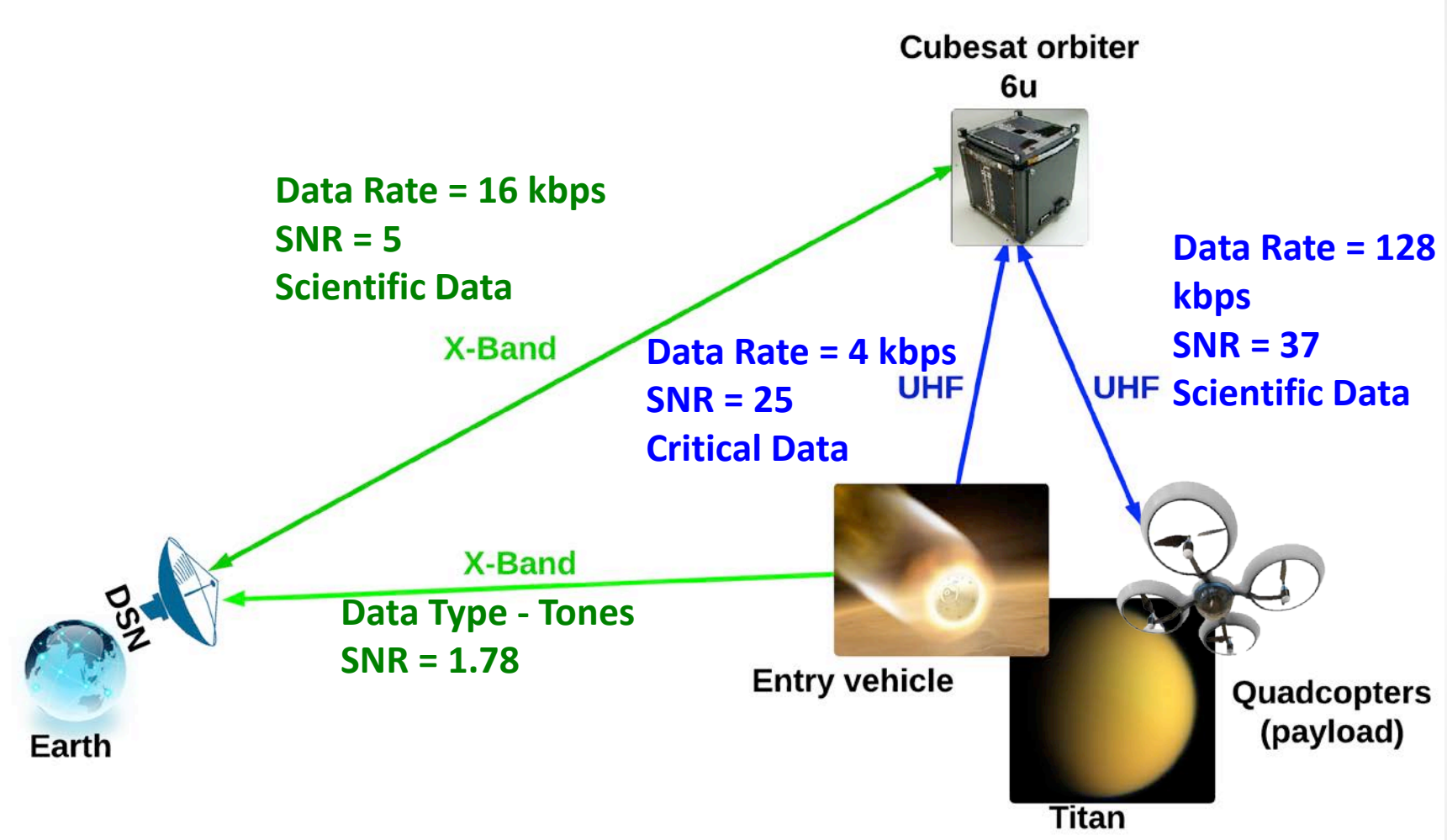
- Power requirement

- Preliminary Packing Considerations

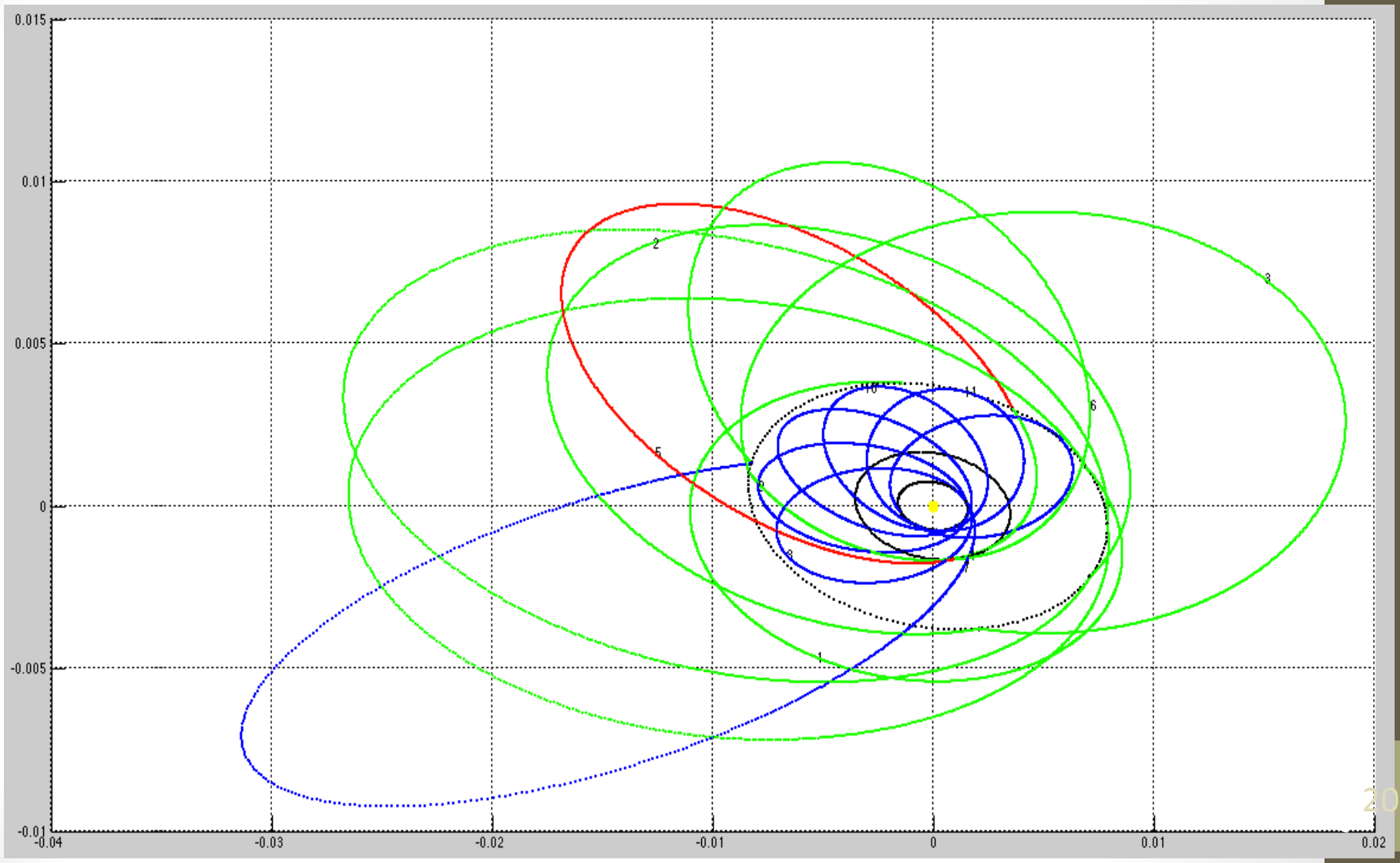
Questions?

Extra Slides

Titan Telecom System Architecture



Trajectory & Aero capture

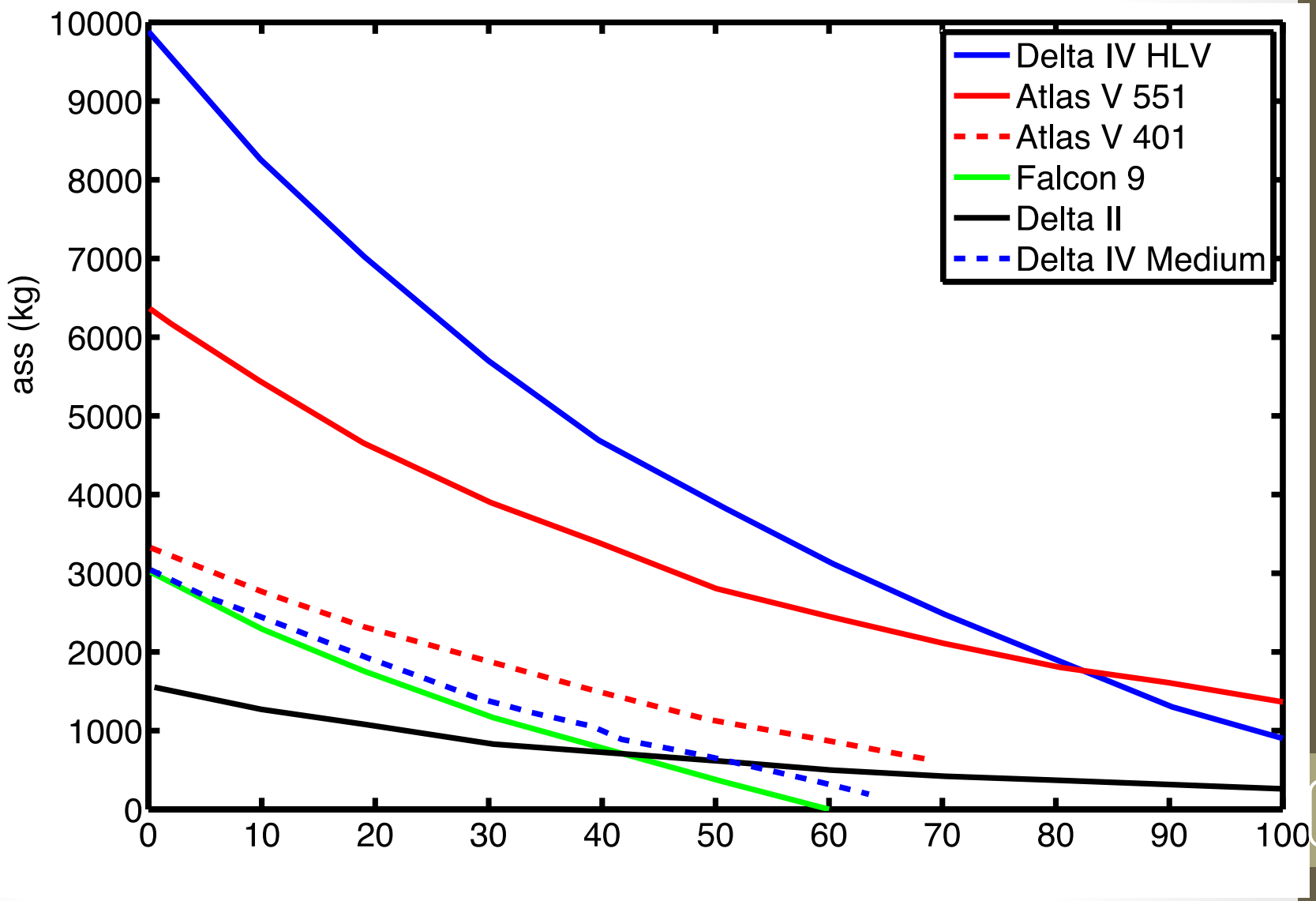


Flyby	Delta V (km/s)	V_{inf} (km/s)	Date	Fly Height (km)
Titan - 1	*0.8135*	*12.7449*	*July 03, 2030*	*1235.8275*
Titan - 2	*-0.0000*	*12.4085*	*August 21, 2030*	*1461.5904*
Titan - 3	*-0.2641*	*12.4085*	*September 24, 2030*	*1212.7278*
Titan - 4	*0.1094*	*12.1447*	*October 31, 2030*	*514.7319*
Titan - 5	***-1.1226***	***10.3680***	***November 05, 2030***	***109.9777***
Rhea - 6	*0.8457*	*11.4682*	*December 04, 2030*	*804.1642*
Titan - 7	*0.0176*	*19.6295*	*January 03, 2031*	*827.7421*
Enceladus - 8	*0.5024*	*10.6743*	*March 03, 2031*	*4.5300*
Titan/Enclds. - 9	*-1.2032*	*28.7497*	*March 10, 2031*	*96.8700*
Enceladus - 10	*0.0000*	*28.7575*	*March 17, 2031*	*768.1000*
Enceladus - 11	*0.0000*	*28.7930*	*March 24, 2031*	*768.5000*
Enceladus - 12	*0.0000*	*28.8448*	*March 31, 2031*	*769.1000*
Enceladus - 13	*0.0000*	*27.8960*	*April 07, 2031*	*769.6000*
Enceladus - 14	*0.0000*	*28.9295*	*April 14, 2031*	*770.0000*
Enceladus Orbit Insertion	*-0.0500*	-	*April 21, 2031*	*122.0000*

Quadcopter Payload Instrumentation

Quad-copter	Instrument	Flight Heritage	Mass CBE (kg)	% Cont.	Mass DMA (kg)	Power CBE (W)	% Cont.	Pow er PA (W)	Data Rate (kbps)	Thermal Limits	Acceleration Limits (g)
QC 1	FTIR Spectrometer	Argus 1000	0.23	30	0.29 9	1.5	30	1.95	13	-40^{0}C – 40^{0}C	20
QC 2	Echo Sounder	Terrestrial	1	30	1.3	20	30	26	0.13	-20^{0}C – 65^{0}C	20
QC 3	Magneto-meter	Multiple	0.25	30	0.325	0.4	30	0.52	13	-50^{0}C – 85^{0}C	20
	Surface Camera (2)	CubeSats	0.4	30	0.52	0.7	30	0.91	1300	-40^{0}C – 40^{0}C	15
QC 4	Decent & Panoramic Camera	MER	0.2	30	0.26	1.5	30	1.95	1300	-40^{0}C – 40^{0}C	15
	Surface Camera	CubeSats	0.2	30	0.26	0.3	30	0.39	1300	-40^{0}C – 40^{0}C	15
QC 5	Sea Properties Package	Huygens	4	30	5.2	10	30	13	130	-40^{0}C – 40^{0}C	15
QCM	Turbidimeter	Galileo Probe	2	30	2.6	10	30	13	0.13	-40^{0}C – 40^{0}C	15

Launch Vehicle Selection



Hypersonic Trajectory Equations

$$\rho(h) = \rho_{0,Titan} e^{-Ah}$$

$$g(h) = g_{0,Titan}\left(\frac{R_{Titan}}{R_{Titan} + h}\right)^2$$

$$v(h) = v_e e^{Ce^{-Ah}}$$

$$C = \frac{\rho(h)}{2\beta A sin(FPA)}$$

$$\beta = \frac{m_e}{C_{dEV} S_{EV}}$$

$$n(h) = -\frac{v_e^2}{g(h)}(h) A C sin(FPA) e^{-Ah} e^{Ce^{-Ah}}$$

$$\Delta s = cot(FPA)\Delta h$$

$$v_{n,max} = 0.606 v_e$$

$$n_{max} = \frac{v_e^2 A sin(FPA)}{2 g_{0,Titan} e}$$

$$h_{n,max} = \frac{1}{A} ln(-2C)$$

Hypersonic Heating Equations

$$q''(h) = c_{Titan}\sqrt{\frac{\rho(h)}{R_n}}v(h)^3$$

$$Q_{Total} = c_{Titan}v_e^2\sqrt{\frac{\pi\beta}{\rho_{0,Titan}AR_n sin(FPA)}}$$

$$q_{max}'' = c_{Titan}\sqrt{\frac{\rho(h_{q'',max})}{R_n}}v_{q,max}^3$$

$$h_{q'',max} = -\frac{1}{A}ln(\frac{\beta A sin(FPA)}{3\rho_{0,Titan}})$$

$$v_{q'',max} = 0.846v_e$$

Hypersonic Regression Rate Equations

$$a_{nit} = (8.441 * 10^{-3})e^{-\frac{2322}{T_w}}$$

$$k_p = \frac{a_{nit}}{4}\left(\frac{8RT_w}{\pi m_s}\right)^{\frac{1}{2}}$$

$$T_w(h) = (\frac{q"(h)}{\sigma\varepsilon})^{\frac{1}{4}}$$

$$J_{CN} = \frac{M_{CN}}{M_N}\rho_N k$$

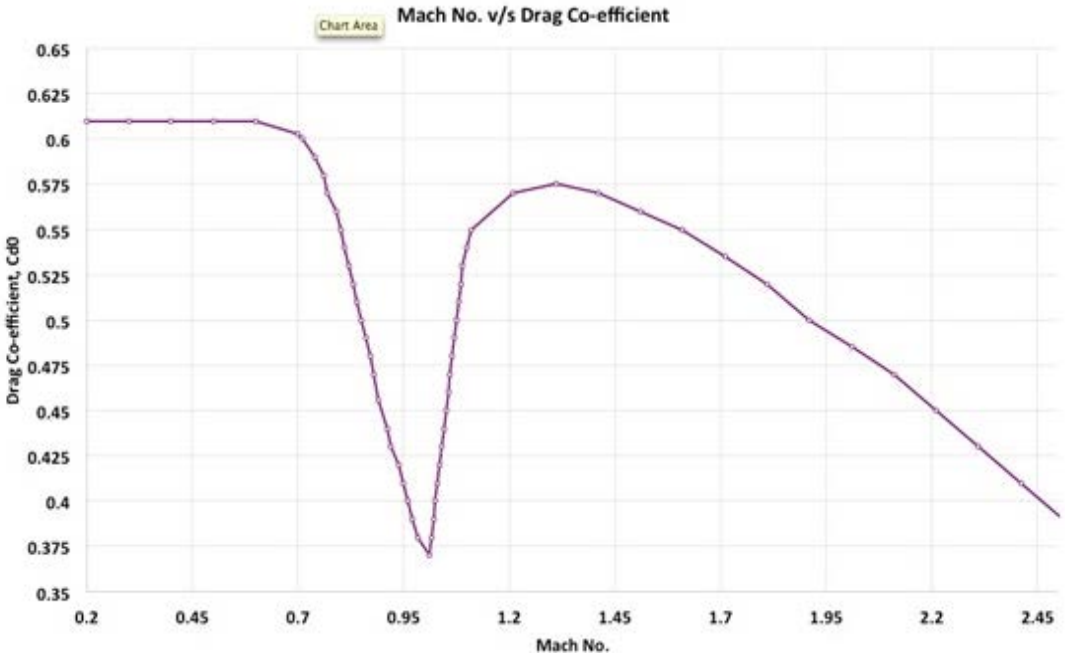
$$\frac{dh}{dt} = v(h)\sin(FPA)$$

$$r = \frac{\frac{M_C}{M_{CN}}J_{CN}}{\rho_C}$$

$$t * sin(FPA) = \int_{h_e}^{h} v_e e^{-Ce^{-Ah}}\, dh \rightarrow h(t)$$

$$S = \int_0^t r dt$$

Supersonic Trajectory Equations



$$\rho(h_i) = \rho_{0,Titan} e^{-Ah_i}$$

$$g(h) = g_{0,Titan}\left(\frac{R_{Titan}}{R_{Titan} + h_i}\right)^2$$

$$h_{i+1} = h_i - v_i \Delta t$$

$$v_{i+1} = v_i + \left(g(h_i) - \frac{\rho_0 e^{-Ah_i} v_i^2}{2m_e}(C_{Dp}S_P + C_{DEV}S_{EV})\right)\Delta t$$

Buoyancy and Power Equations

$$B_F = \rho_f g V_{displacement}$$

$$F_{weight} = \frac{m_{s/c}}{\rho_f}$$

$$floatation\ on\ surface \rightarrow B_F = F_{weight}$$

$$V_{discplacement} = \frac{m_{s/c}}{\rho_f}$$

$$P_{quad} = \sqrt{\frac{F_{th}^{\frac{3}{2}}}{2\rho\pi R_{quad}^2}}$$

Quadcopter Power Source

Cm			
Power (We)	**Mass (g)**	**Volume (cm3)**	**Power Density(We/g)**
5	82.7	123.4	0.06
10	109.6	145.3	0.09
15	134.5	162.1	0.11
Am			
Power (We)	**Mass (g)**	**Volume (cm3)**	**Power Density(We/g)**
5	731.7	393.5	0.06
10	1362.86	554.9	0.09
15	1986	691.2	0.11
PuO2			
Power (We)	**Mass (g)**	**Volume (cm3)**	**Power Density(We/g)**
5	249.4	226.8	0.02
10	423	296.5	0.0236
15	592.2	353	0.0253

RTPV Radioisotope Comparison[1]

CAD Model of the RTPV[1]

[1]Center for Space Nuclear Research, Idaho National Labs

Future Work

→ Next stage of the process is to begin to asses the following key criteria

1) CFD modeling of the quadcopter design
   - Model wind speeds
   - Atmosphere
2) Quadcopter fabrication to empirically test
   - buoyancy
   - waves balancing
3) Docking and Charging Methods

MEL & PEL

Subsystem	Mass CBE (kg)	% Cont.	Mass DMA (kg)	Power CBE (W)	% Cont.	Power PA (W)
Structures & Mechanism including Parachute	46.945	30	61.03	5	30	6.5
Telecom	8	30	10.4	100.25	30	130.325
Quadcopters carrying their individual payloads	40	30	52	350	30	455
Thermal Control	1.6	30	2.08	41.77	30	54.301
Command & Data Handling	0.25	30	0.325	0.6	30	0.78
Power Electronics System and additional instrumentation	14.5	30	18.85	0.3	30	0.39
Thermal Control inside the entry vehicle	13.32	30	17.316	5	30	6.5
Heat Shield	75.4	30	98	0.5	30	0.65
Available Power from QC Swarm Payload				**350**	**0**	**350**
Total	**~200**	**30**	**260**	**~153.5**	**30**	**~200**

Quadcopter Power Budget

Power (W)	QCM	QC1	QC2	QC3	QC4	QC5
Battery Power available	**100**	**40**	**70**	**40**	**40**	**60**
Propulsion (max power)	28	12.5	12.5	12.5	12.5	28
Telecom	5	1	1	1	1	1
QC to QC Telecom	$1.00e^{-03}$	$1.00e^{-03}$	$1.00e^{-03}$	$1.00e^{-03}$	$1.00e^{-03}$	$1.00e^{-03}$
Payload Instrumentation	13	1.95	26	0.52	2.34	10
Thermal	5	5	5	5	5	5
C&DH	0.6	0.6	0.6	0.6	0.6	0.6
Current Best Estimate	62.60	25.55	49.60	24.12	25.94	49.6
Contingency 30%	18.78	7.37	14.58	6.94	7.48	8.38
DPA (W)	**86.38**	**36.92**	**68.18**	**35.06**	**37.42**	**57.98**
Operation time (min)	**36.86**	**94.00**	**47.48**	**99.81**	**92.53**	**96.00**

Telecommunication

Link Parameters	Direct to Earth	Entry Vehicle To Orbiter	Mother Quadcopter to Orbiter	Orbiter to DSN
Tx Antenna	Patch	Patch	Low Gain Patch Antenna	1.732 meters HGA
Tx Power (W)	100	0.24	5	500
Frequency (GHz)	8.4 X-Band	0.45 (UHF Band)	0.45 (UHF Band)	8.4 X-Band
Data Type	Tones	Critical Data	Scientific Data	Scientific Data
Data Rate (kbps)	Carrier Signal	4	128	16
EIRP (dB W)	56	29.97	≈13	69.4
Distance (km)	$1.6e^{9}$	1300	1300	$1.6e^{9}$
Rx Antenna	70 meters HGA	1 meter LGA	1.732 meters HGA	34 meters HGA
SNR (dB)	1.78	24.9	≈37	≈5
Margin	1.78	15.9	$10e^{-6}$ (BPSK)	$10e^{-6}$ (BPSK)

Testing and Analysis

- TPS testing using Arc Jets.
  - Interactive Heating Facility in NASA AMES.
    - Convective heating rates of up to 2555 KW/m^2, surface pressures of 121.6 kPa, and bulk enthalpies of 46.5 MJ/kg .
- Parachute testing not needed given that Viking's parachute is used
  - Extensively tested

- Load, Vibration, Acoustic and Shock test required to prove entry vehicle and payload's sturdiness
  - Low TRL quadcopters need to be space certified
  - Vibration and Acoustics Test Facility in NASA's Johnson Space Center
    - Vibrations of up to 2000Hz and 4000lbf, and acoustic sounds of up to 10000Hz
- Temperature Test for the 94K surface temperature.
  - The Polymer Laboratory in NASA's Johnson Space Center
    - Ability to perform material testing of loads up to 35000 lbs. in temperatures as low as -300°F

Ref: Jean- Marc Bouilly, *Thermal Protection System of the Huygens Probe During Titan Entry: Flight preparation and lessons Learned*, CFD Analysis process, NASA

Entry Type Trade Study

Ballistic over Lifting Body Entry	Orbital over hyperbolic Entry
Large landing ellipse	Mission Architecture includes Orbiter
Reduced cost and complexity	Reduces any interplanetary trajectory errors
No Guidance, Navigation and Control	
High altitude deployment of Quadcopters from EDL vehicle	Determines atmospheric conditions before EDL
Reduces total heat load	