National Aeronautics and Space Administration
Goddard Space Flight Center

HYDROGEN-FILLED TITAN AEROBOT BALLOON SYSTEM (TABS) – DESIGN AND FEASIBILITY

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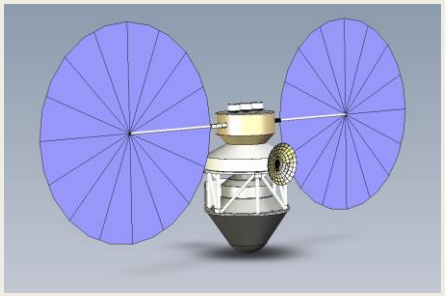
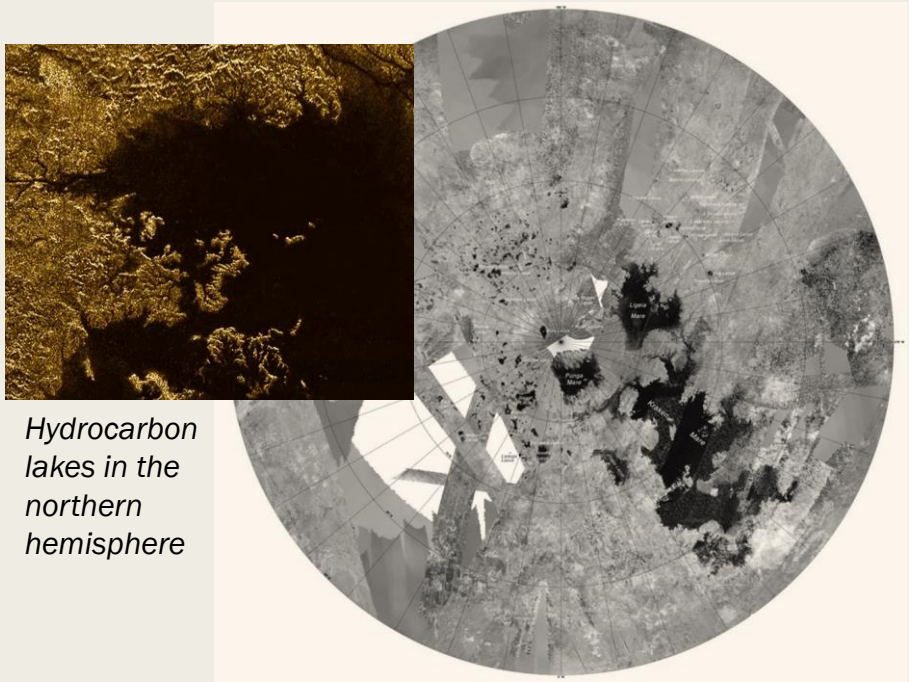


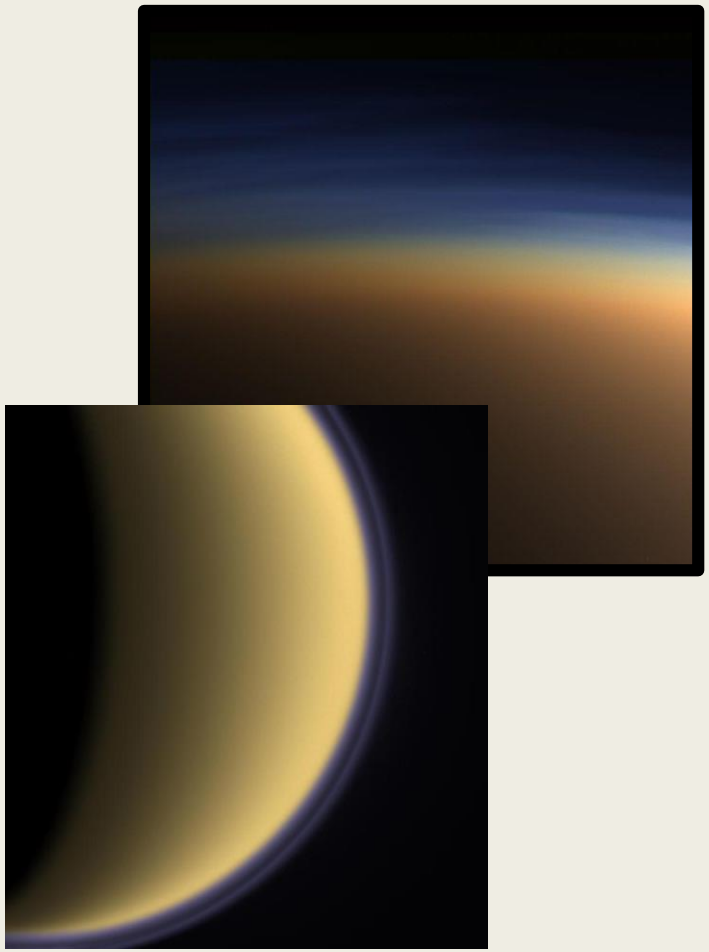
Systems Engineering Seminar Presentation, 20 March 2017

Why Saturn Moon's Titan?



Hydrocarbon lakes in the northern hemisphere

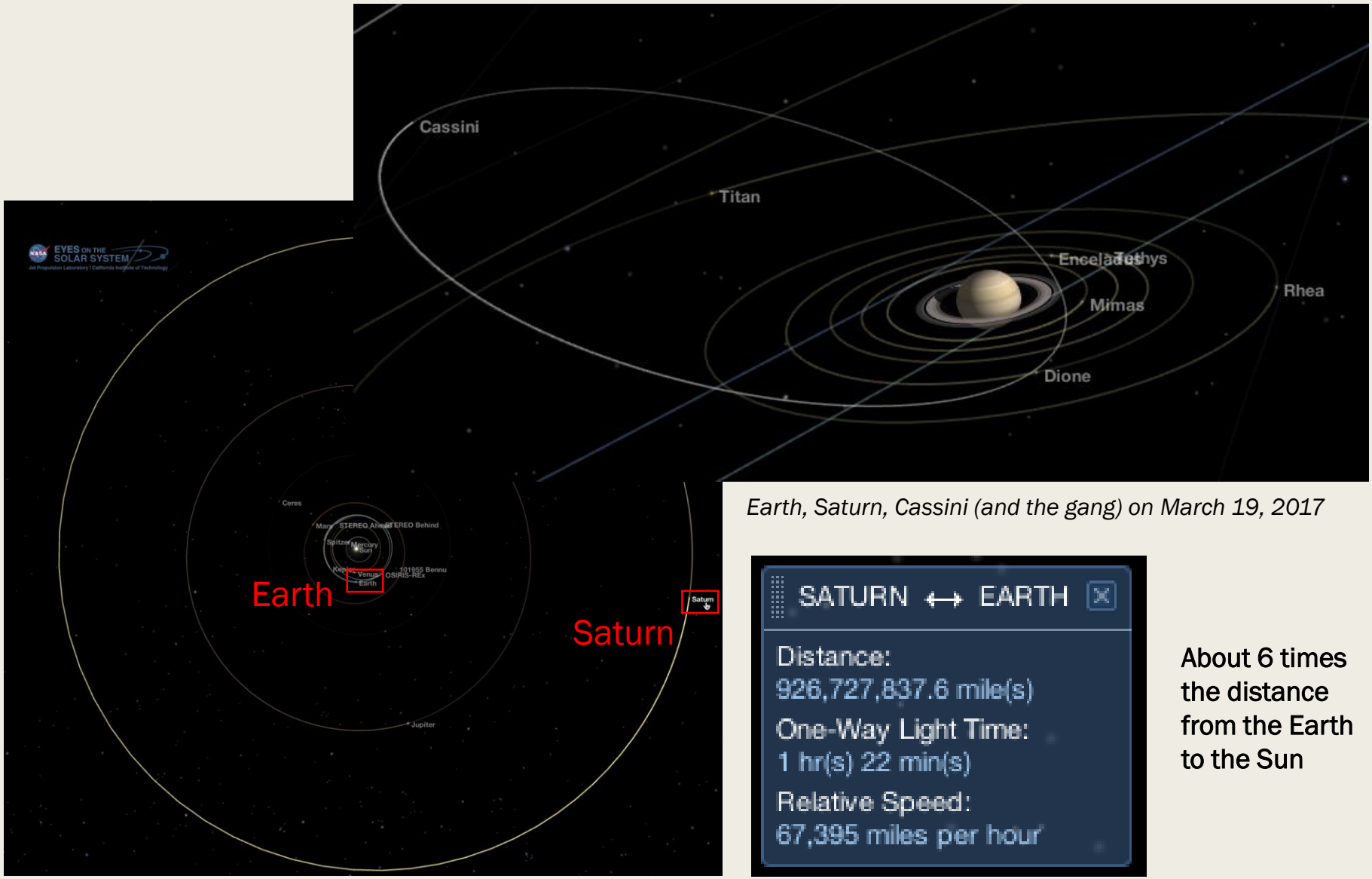
Atmospheric Organic Hazes



- Hydrocarbon (Methane/Ethane) lakes.
- Pre-biotic processes, with hydrocarbon (rather then water) cycle.
- A cryogenic world, with a Nitrogen-rich atmosphere much like Earth's.

https://www.nasa.gov/mission_pages/cassini/main/index.html

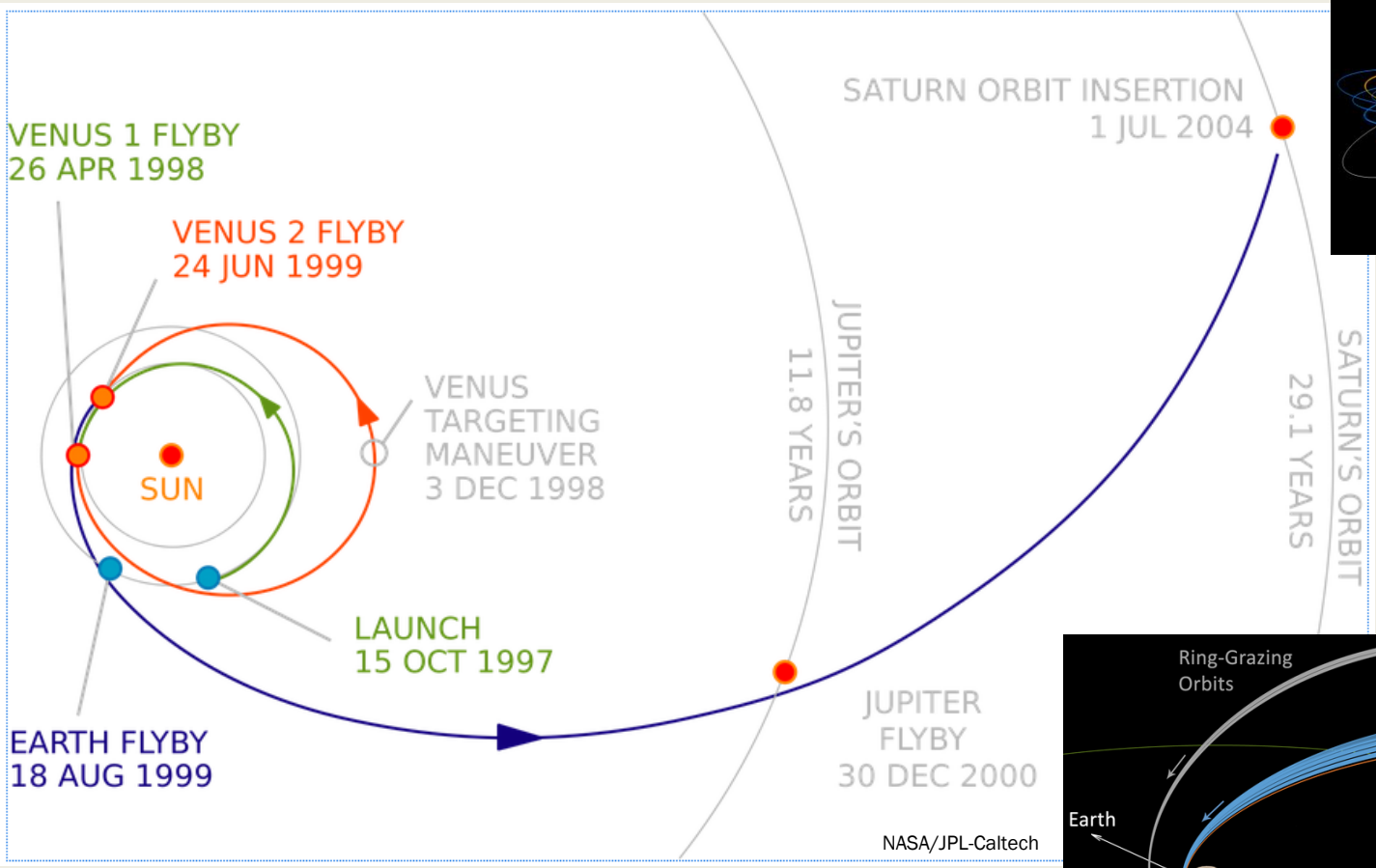
An Introduction to Distance Scales



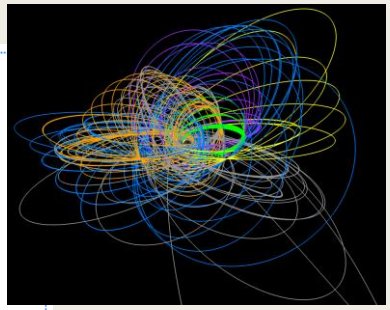
Earth, Saturn, Cassini (and the gang) on March 19, 2017

About 6 times the distance from the Earth to the Sun

How did Cassini get there?

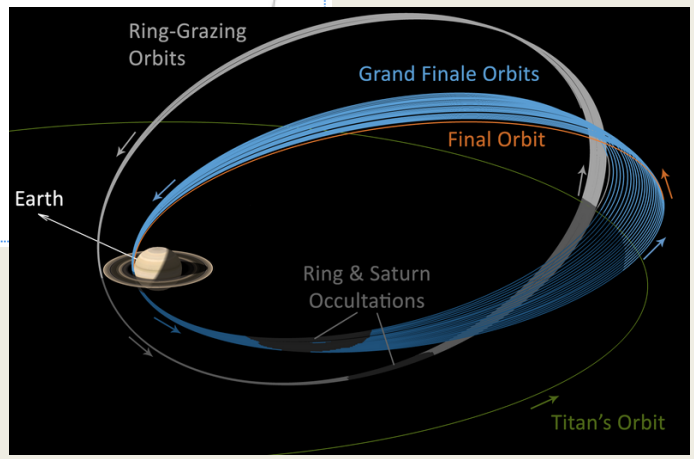


From Earth to Saturn



Mission Orbits Around Saturn

Final Orbits



7-year trip… We need a "warp" drive !

Background

- This presentation is based on research carried out during my dissertation work at the University of Stuttgart in Germany, from 2009 to 2012*.
- This work developed a mission concept that demonstrated the *only known and detailed feasible alternative to the NASA/ESA Titan Montgolfier (hot air balloon) concept.*
- Provided an *empirical contribution to the field of hyperbolic entry ablator thermal protection system (TPS) material research.*
- The design *left the door open for international cooperation* in an area where pooling institutional resources contribute to mission success

* Esper, J., "Mission Design and Technology for a Titan Aerobot Balloon System (TABS)", PhD Dissertation, The University of Stuttgart, Germany, March 2012

Objectives

- Develop an end-to-end mission concept that includes a direct entry trajectory at Titan.
- Focus on systems and technologies that both **enable** and **enhance** a successful Titan Balloon Aerobot.
  - *Develop a mission implementation that uses a lighter-than-air buoyant gas.*
  - *Carry out experimental research to develop a TPS ablative material using current commercial and available materials.*

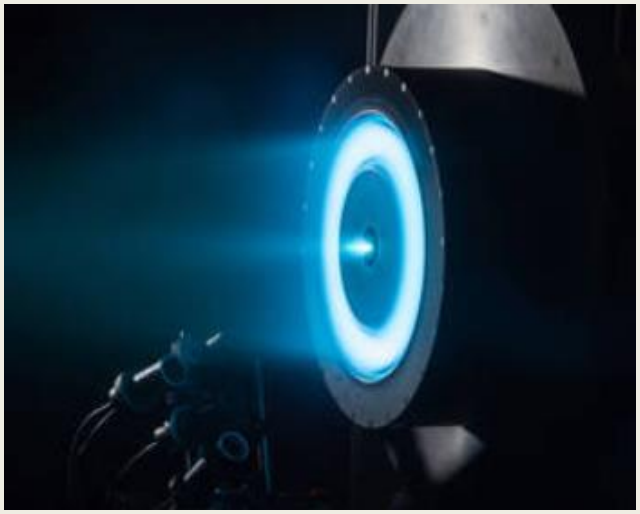
Key Technology Functional Areas

- In the technology area, this research follows the Outer Planets Assessment Group (OPAG-2009*) recommendations for technology development. This report recommends the following emphasis for a Titan in-situ sampler (E=enabling; e=enhancing):
  - *Electric Propulsion (e)*
  - *Radioactive Power System – RPS (E)*
  - *Expanded Ka capability (OPAG = e) – for our purposes, and given a stand-alone mission, this is an enabling capability (E)*
  - *Planetary mobility (E)*
  - *Autonomy (OPAG = e) – without autonomy, TABS could not be flown given the great distances involved. Hence it is considered an enabling capability (E)*
  - *Extreme environments (OPAG = e) – for a balloon mission this technology capability remains a mission enabling capability (E)*
  - *Entry systems (includes TPS, parachutes, etc.) (OPAG = e) – for certain application/system combinations (TABS TPS), entry systems may also represent an enabling capability (E)*
  - *In situ sensing of surface and atmospheres (E)*
  - *Components and miniaturization (E)*
  - *Remote sensing (e)*

* Beauchamp, P. M.: "Technologies for Outer Planet Missions: A Companion to the Outer Planet Assessment Group (OPAG) Strategic Exploration White Paper, September 12, 2009.

Electric Propulsion – mission enhancing technology

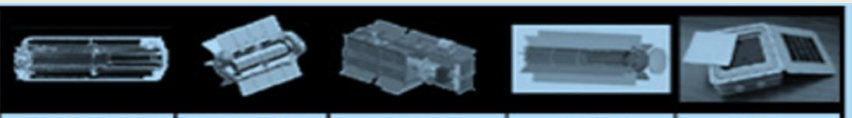
- Maximizes payload and reduces flight times. From a Neptune/Triton mission study*, the most effective approach to reaching an outer planet is to design a two-stage system, with SEP in the inner solar system, and chemical propulsion beyond the orbit of Mars.



* Esper J., "The Neptune / Triton Explorer Mission: A Concept Feasibility Study," Master's Thesis, The George Washington University, Washington, D.C., January 2000.

Radioactive Power System (RPS) – mission enabling technology

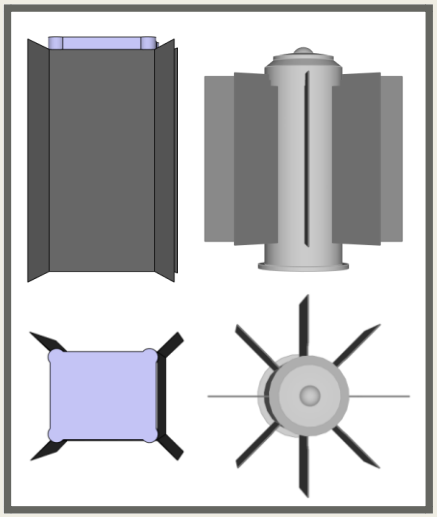
- TABS leverages previous US Department of Energy (DOE) and NASA work in an Advanced Stirling Radioisotope Generator (ASRG).
- Although this was the status in 2010, the ASRG project has since been superseded by the availability of Pu-238 well into the future, and the MMRTG proven technology. Nonetheless, "the hardware procured under {DOE} activity {has been} transferred to the Glenn Research Center to continue development and testing of the Stirling technology." (J. Green, 2014).
- The about 20kg of additional mass would have to come from the contingency/ margin allocations, if ASRG technology remains unattainable at mission start.



	GPHS-RTG Past	MMRTG Present	ASRG In Development	ARTG Future	TPV Future
Electric Output, BOM, W_e	285	125	~140-150	~280 to 420	~38-50
Heat Input, BOM, W_e	4500	2000	500	3000	250
RPS System Efficiency, BOM, %	6.3	6.3	~28-30	~9-14	~15-20
Total System Weight, kg	56	44.2	~19-21	~40	~7
Specific Power, W_e/kg	5.1	2.8	~7-8	~7-10	~6-7
Number of GPHS Modules	18	8	2	12	1
GPHS Module Weight, kg	25.7	12.9	3.2	19.3	1.6
^{238}Pu Weight, kg	7.6	3.5	0.88	5.3	0.44

Acronym Key: ARTG, Advanced Radioisotope Thermal Generator; ASRG, Advanced Stirling Radioisotope Generator; BOM, Beginning of Mission; GPHS, General Purpose Heat Source; MMRTG, Multi-Mission Radioisotope Thermoelectric Generator; RTG, Radioisotope Thermal Generator; TPV, Thermophotovoltaic.

ASRG MMRTG



Expanded Ka Capability – mission enabling technology

- Direct-to-Earth link requires the use of Ka-band and higher frequencies in order to effectively transfer relatively large amounts of information over vast distances typical to the outer planets. Inflatable / small package antenna technology is one consideration, but was not required in this research based on the link analysis for a one-meter aperture parabolic antenna.

Planetary Mobility – mission enabling technology

- A hot air balloon was identified by a joint NASA/ESA study group as a key element in a comprehensive Titan exploration plan.
- This research explores a Hydrogen-filled balloon alternative that can leverage extensive experience and simplifies the balloon system, in particular in its deployment and initial survival.

Hot Air Balloons

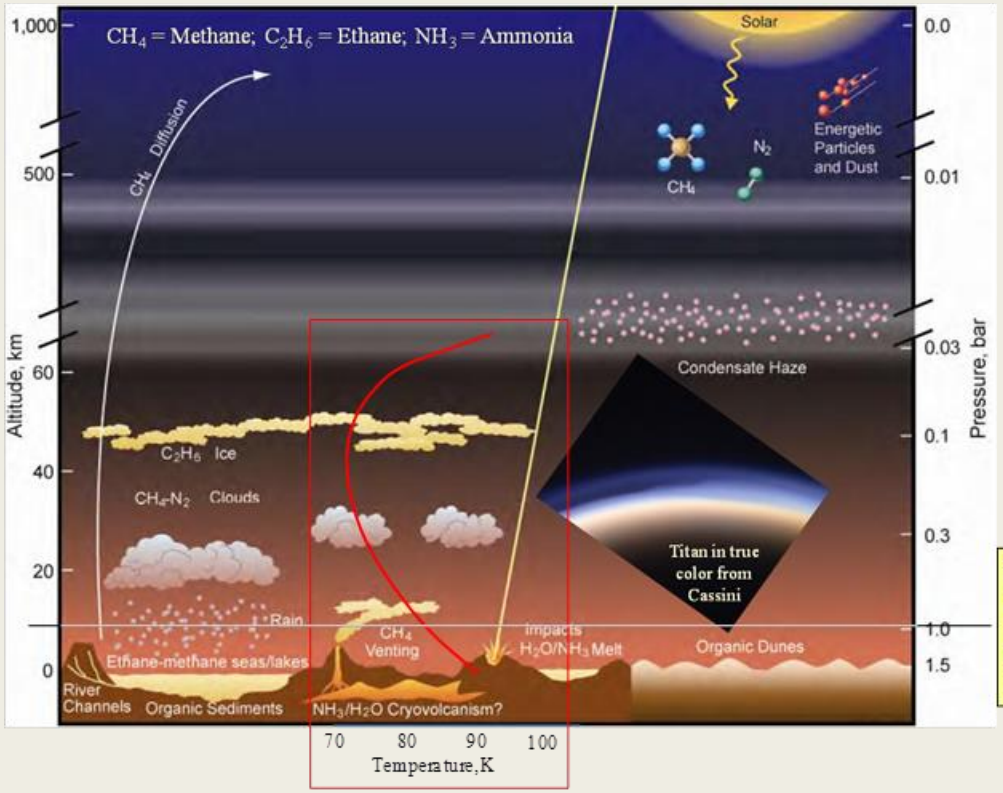
Super Pressure Scientific Balloon in Flight

Super pressure balloon construction

J. Esper

Extreme Environments – mission enabling technology

- Low temperatures impact chemical, electronic, and mechanical components, sensors and actuators, and balloon materials.



Titan is shrouded by a dense, cold atmosphere, comprised primarily of nitrogen (98.4%) and methane (1.6%) with traces of argon and hydrocarbons. The organic compounds are formed as the methane is destroyed by sunlight.

Balloon Operating Conditions
Nominal Altitude: 10 km
Temperature: -189°C (84K)
Pressure: 884 mbar
Wind Speed: 4 km/hr

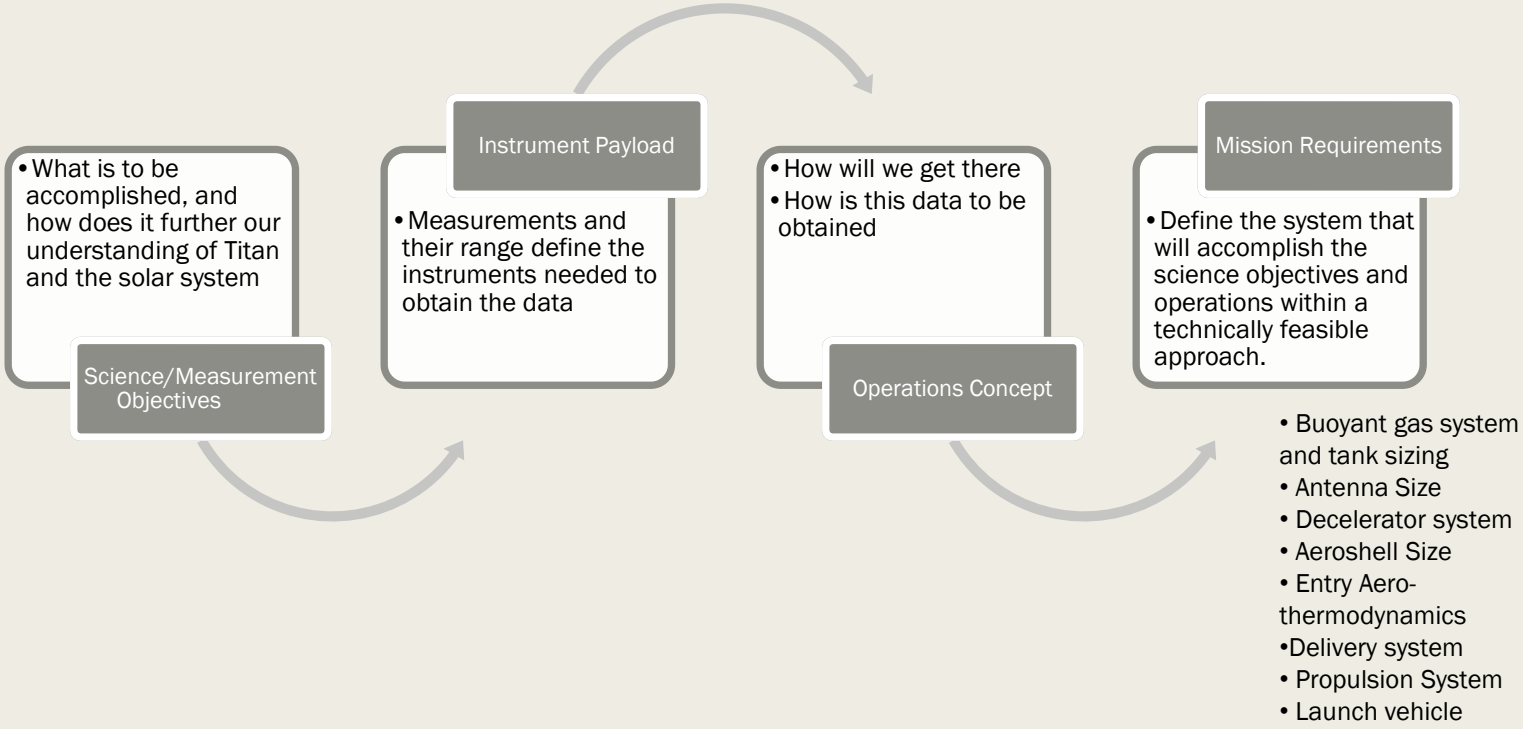
Entry Systems – mission enhancing and enabling technology

- Insofar as materials already exist that can handle extreme environments, improvements can be certainly enhancing.
- High entry speeds thermal ablators either need additional qualification, or currently do not exist in a manner that allows repeatable manufacturing.
- Availability of these materials then become enabling for certain outer planetary (and Earth return) entry missions at hyperbolic speeds.

Phoenix lander parachute descending through the Martian atmosphere as seen by the Mars Reconnaissance Orbiter HiRISE camera (May 25, 2008).

Methodology

- Follow a traditional systems engineering approach, sprinkled with creative spices and a good measure of irreverence to consensus thinking.



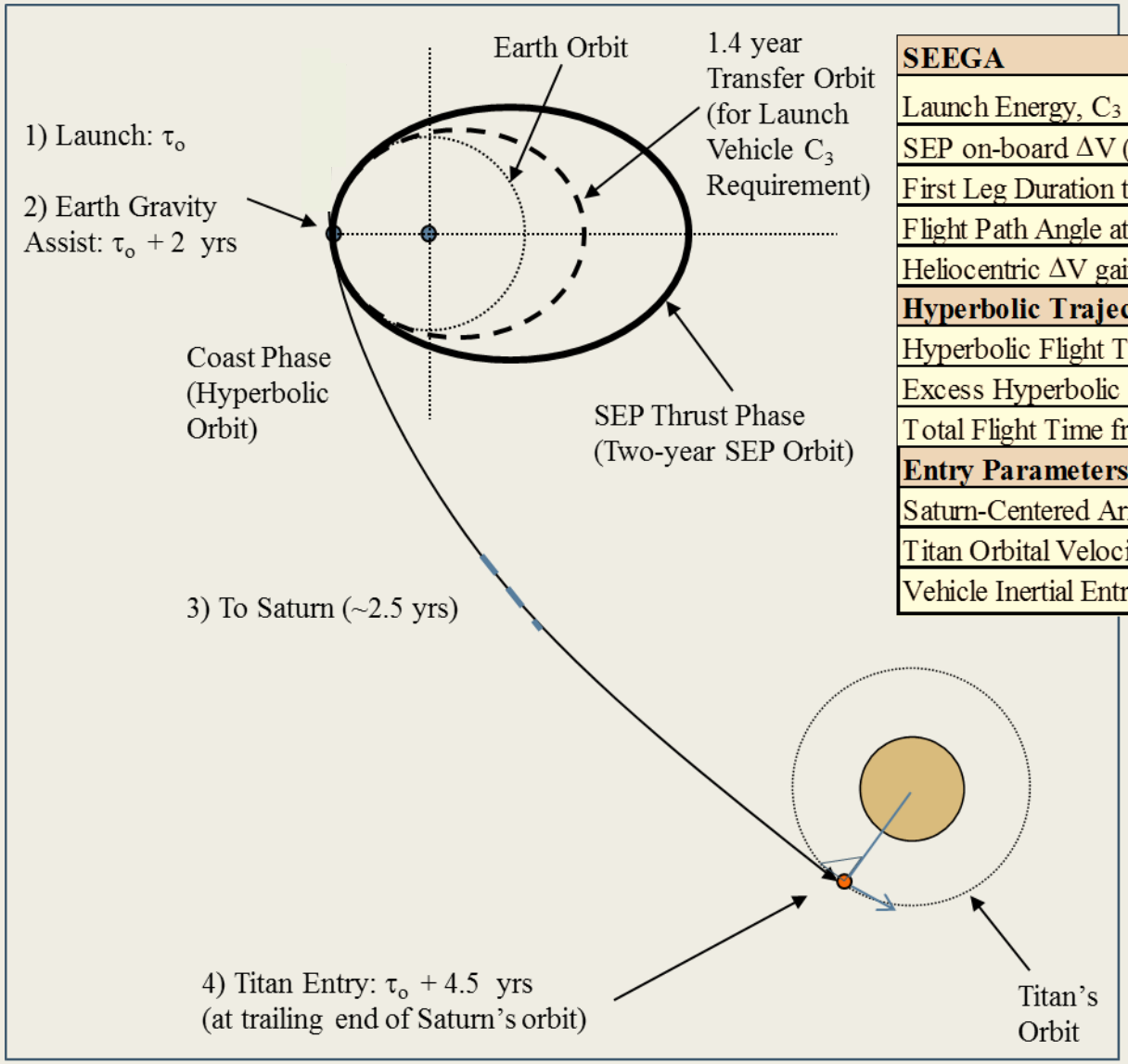
Scientific Objectives and Science Instruments

- TABS follows the recommendation for a payload suite as defined in the TSSM Study Report* for the balloon system component.
- Definition of this payload only serves to constrain the engineering implementation

Measurement Objectives	*Science Instrument*
Stereo surface characterization and atmospheric phenomena.	Visible Imaging System Balloon. Three wide angle and one narrow angle cameras.
Composition and temperature mapping of surface at regional and local scale. Composition and optical properties of haze and clouds.	Balloon Imaging Spectrometer. Imaging diffraction grating spectrometer.
Methane/ethane mole fraction, noble gas concentration at 10s of ppb. Characterises molecules in atmosphere above ppm levels. Chemical composition of aerosols.	Titan Montgolfière Chemical Analyser. Ion trap mass spectrometer.
Temperature profile, atmospheric density and pressure measurements during entry and throughout the whole mission.	Atmospheric Structure Instrument / Meteorological Package. Accelerometers, temperature sensors, capacitive sensors
Lightning detection	Titan Electric Environment Package Balloon
Magnetic field characterization	Magnetometer
Sound for ice underneath the crust	Titan Radar Sounder
Space plasma and radio physics	Montgolfière Radio Science Transmitter

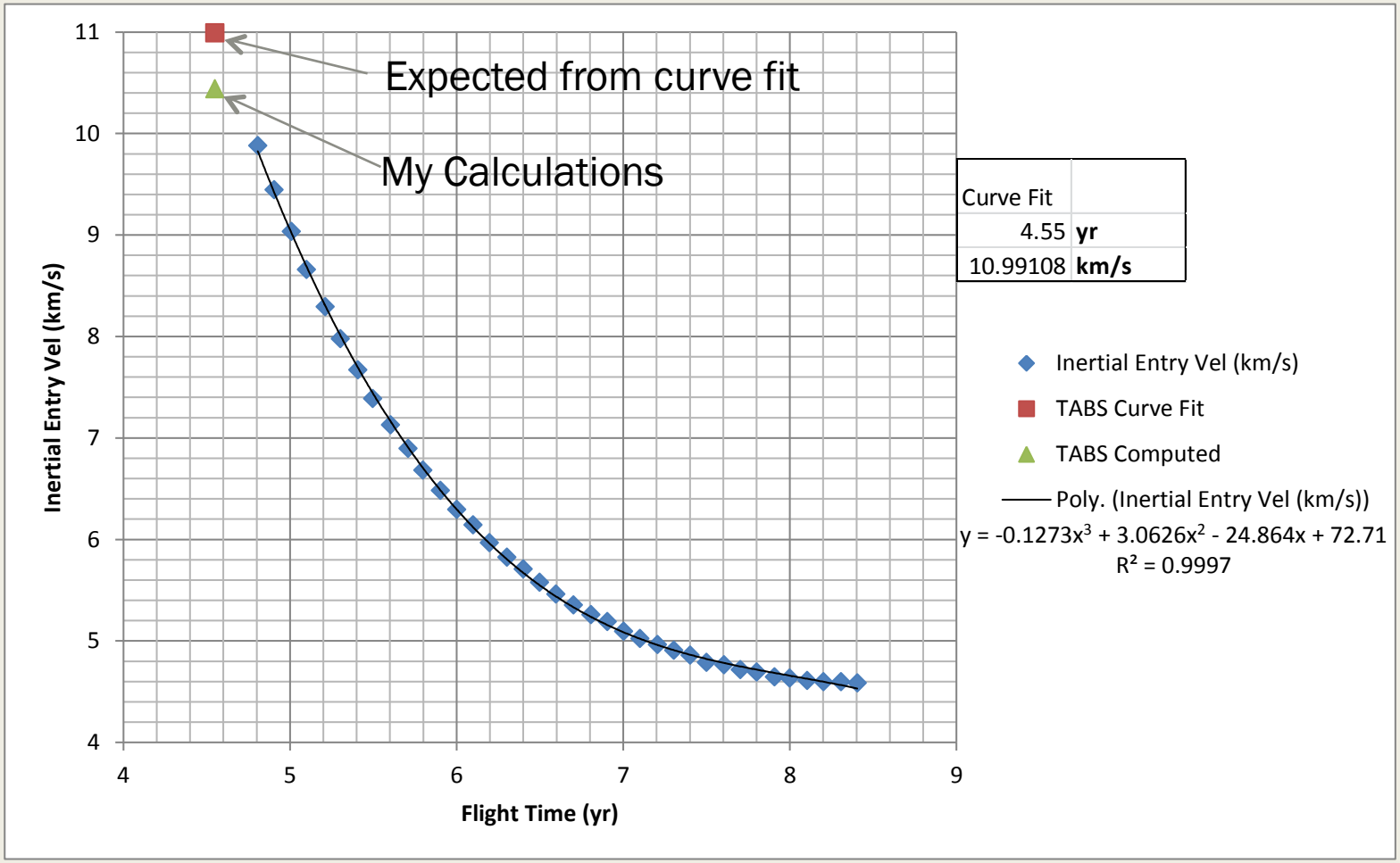
* Titan Saturn System Mission (TSSM), Final Report on the NASA Contribution to a Joint Mission with ESA, January 30, 2009, Task Order #NMO710851.

Trajectory Result



SEEGA	
Launch Energy, C_3 (km^2/s^2)	8.1
SEP on-board ΔV (km/s)	2.3
First Leg Duration to EGA (yr)	2.0
Flight Path Angle at Earth Swing-by (deg)	5.5
Heliocentric ΔV gained (km/s)	7.2
Hyperbolic Trajectory	
Hyperbolic Flight Time (yr)	2.5
Excess Hyperbolic Velocity at Saturn (km/s)	13.9
Total Flight Time from Launch (yr)	4.5
Entry Parameters	
Saturn-Centered Arrival Velocity (km/s)	16.0
Titan Orbital Velocity at Arrival (km/s)	5.6
Vehicle Inertial Entry Speed (km/s)	10.4

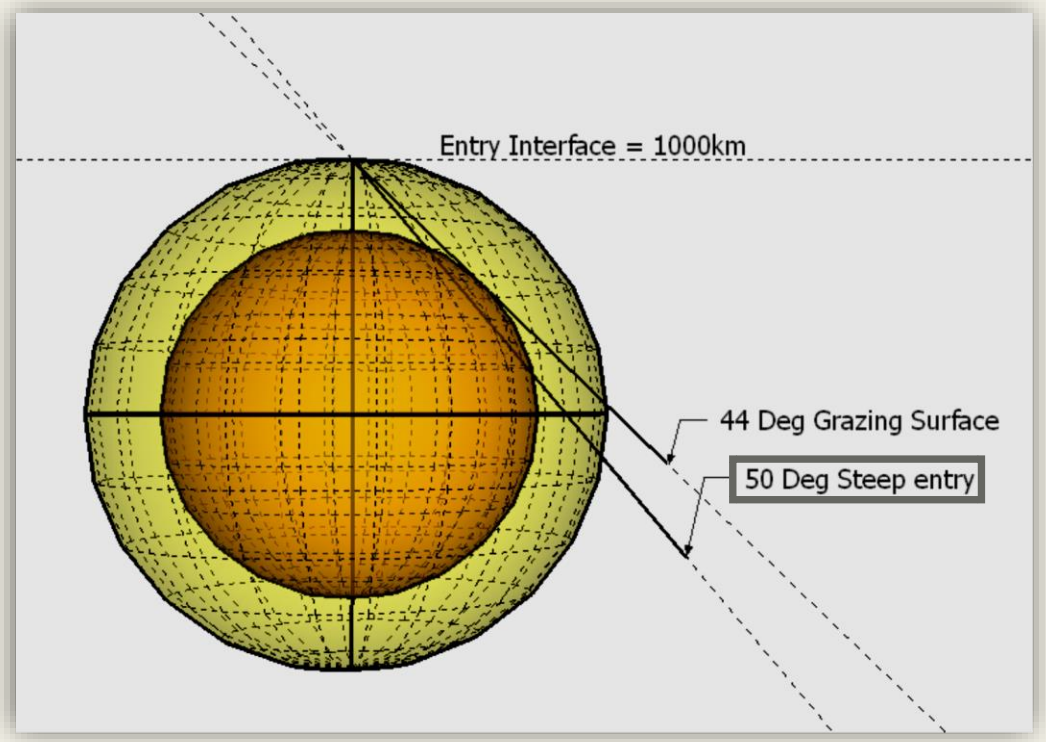
Trajectory and Entry Speed Validation



*Noca, M., R.W. Bailey: "Titan Explorer Mission Trades from the Perspective of Aerocapture, preprint 2005

Entry Flight Path Angle

- The entry flight path angle needs to be defined in order to ensure TABS neither skips-off the atmosphere, nor it crashes onto the surface.
- It is estimated first from a purely geometric account, and iterated as aerothermodynamic parameters are computed so as to provide a reasonable balance between deceleration and heat load inputs.



Balloon Deployment Altitude

- One must select the most benign environment for deployment and operations of the balloon at Titan.
  - *That means choosing the best combination of pressure, temperature, and atmospheric conditions, in particular wind speeds and shear.*
- From wind data obtained by Huygens, the regions below 5 km has winds below 1 m/s, reaching close to zero at the surface.
- However, for regions below ~6 km precipitation is more likely, and can complicate the system design. Higher altitudes require a larger balloon for a given payload mass.
- Hence, the recommendations from the TSSM study are followed, and a nominal height of 10 km is baseline in this work.

Basic Balloon Equation and Types

- From Archimedes principle of floatation and the ideal gas law, the general equation describing all types of balloons and their payload carrying capacity is

$$M_p := \rho_a \cdot V_b \cdot \left[1 - \left(1 + \frac{\Delta P}{P_a} \right) \cdot \frac{\mu_g \cdot T_a}{\mu_a \cdot T_g} \right] - M_b$$

M_p = Payload mass; M_b = balloon mass, ρ_a = ambient density; V_b = balloon volume; ΔP = pressure gradient inside-outside balloon; P_a = ambient pressure; T_a = ambient temperature; T_g = buoyant gas temperature; μ_g = molecular weight of buoyant gas; μ_a = molecular weight of ambient gas.

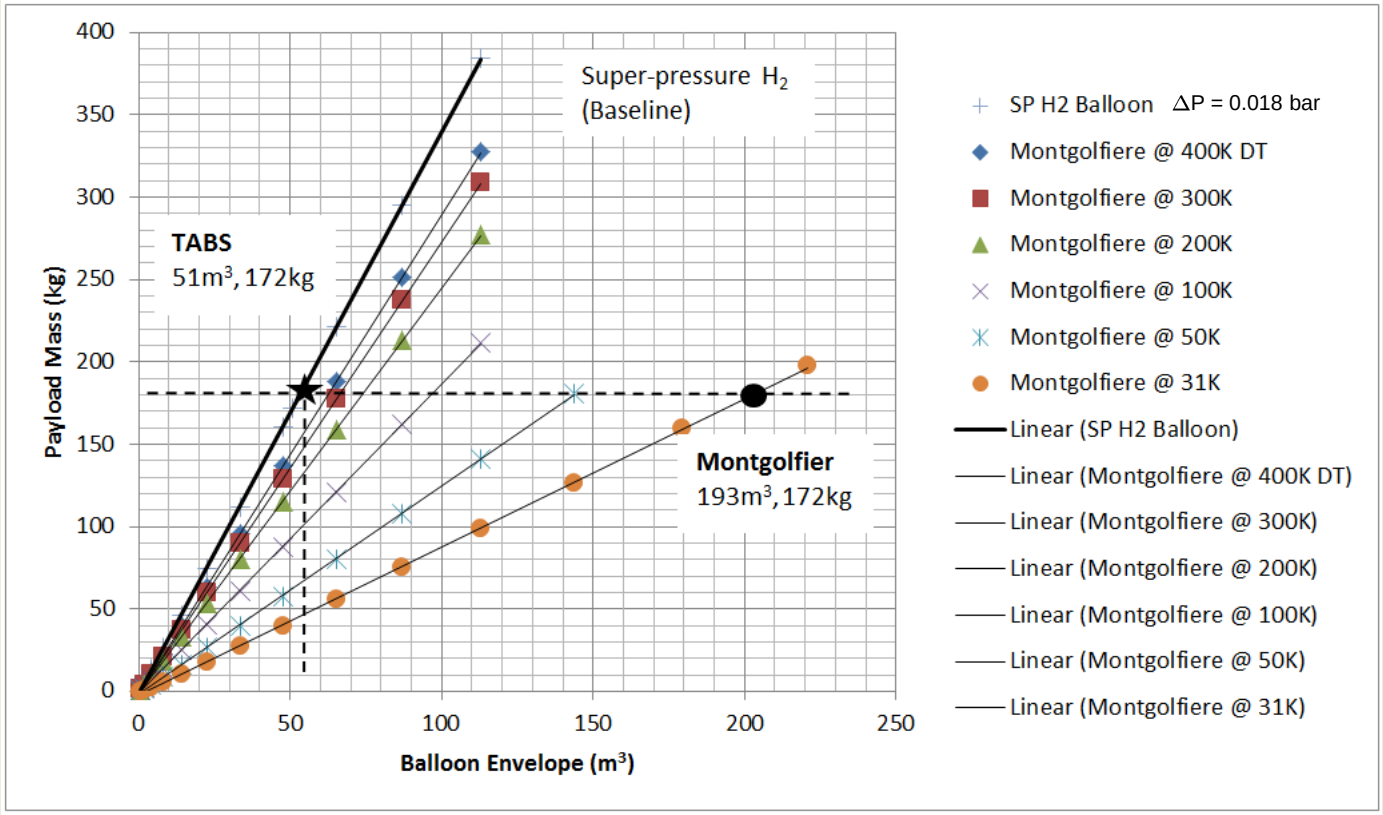
Super-Pressure Balloon $0 < \Delta P = 0$ Zero-Pressure Balloon

Ambient Gas Balloon $\mu_g = \mu_a$ $\Delta P = 0$ $T_g > T_a$

Montgolfier balloon

Balloon Type Performance: SP vs Montgolfier Payload

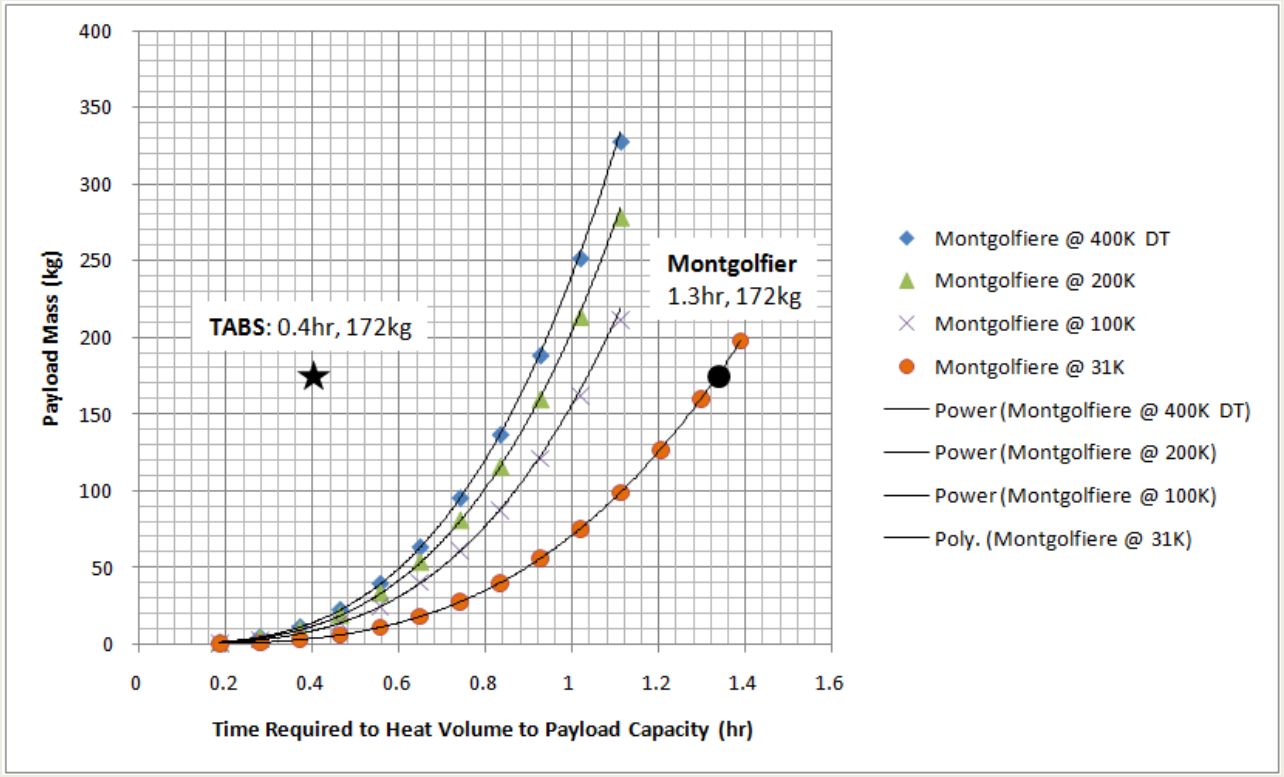
The SP H_2 balloon comes ahead in payload carrying capability for a given envelope. This is important, as the difference is rather large: 51 versus 193 cubic meters.



Titan at 10 km altitude, 0.884 bar, 84K

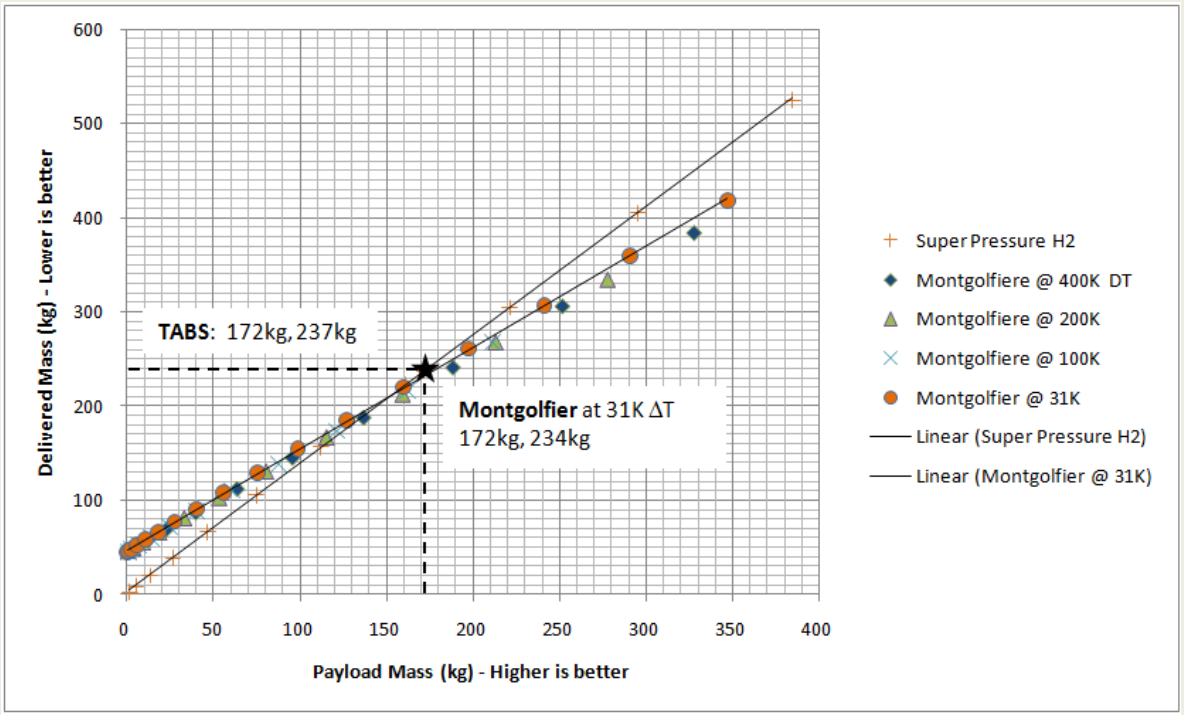
Inflation Time

- The SP H_2 balloon is ahead of the Montgolfier by about 1 hour.
- A considerable advantage, considering that the longer time to inflate, the longer the loose material will be exposed to aerodynamic loading and possible tear.



Delivered Vs. Payload Mass

- The most efficient system would maximize the payload mass, and minimize the delivered mass to the floating altitude.
  - *For the SP H_2 gas case, the delivered mass includes the mass of the gas, balloon, tank, and payload.*
  - *For the Montgolfier case, the delivered mass includes the mass of the balloon, MMRTG, and payload.*

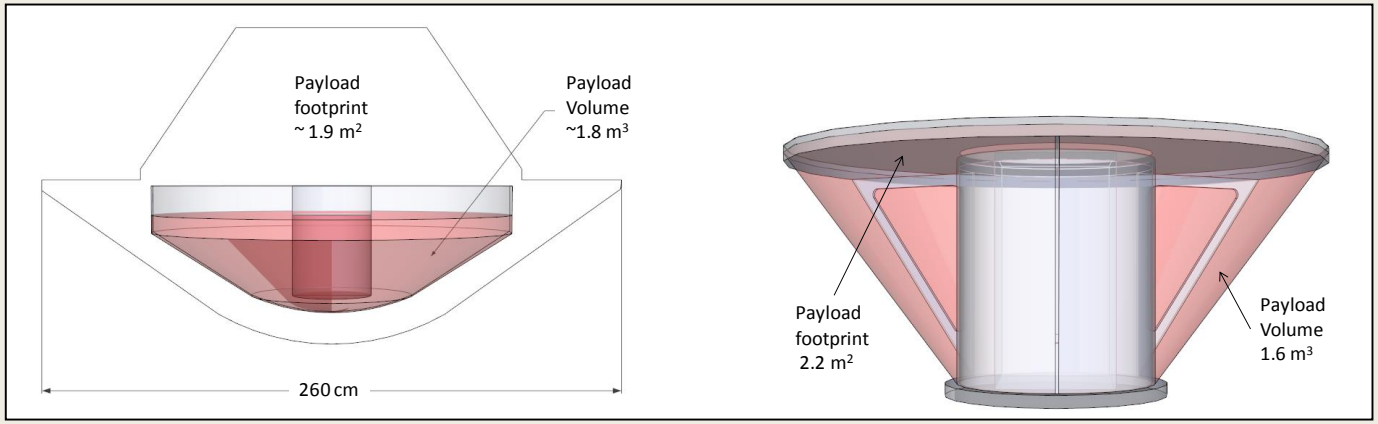


Balloon Trade Conclusion

- A system-level look at the overall mission, which must take into consideration not only longevity, but also the likelihood of mission success, begins to put into question whether a Montgolfier is the best approach.
- Comparable payload masses with smaller balloon envelopes, shorter inflation times, and relatively well understood technology with clear deployment and operational approaches, all coalesce into favoring a SP H_2 approach.

Basic Entry Probe Packaging and Layout

- The basic TABS size was derived from the volume and instrument footprint area allocations given in the TSSM in-situ probe instrument suite*.



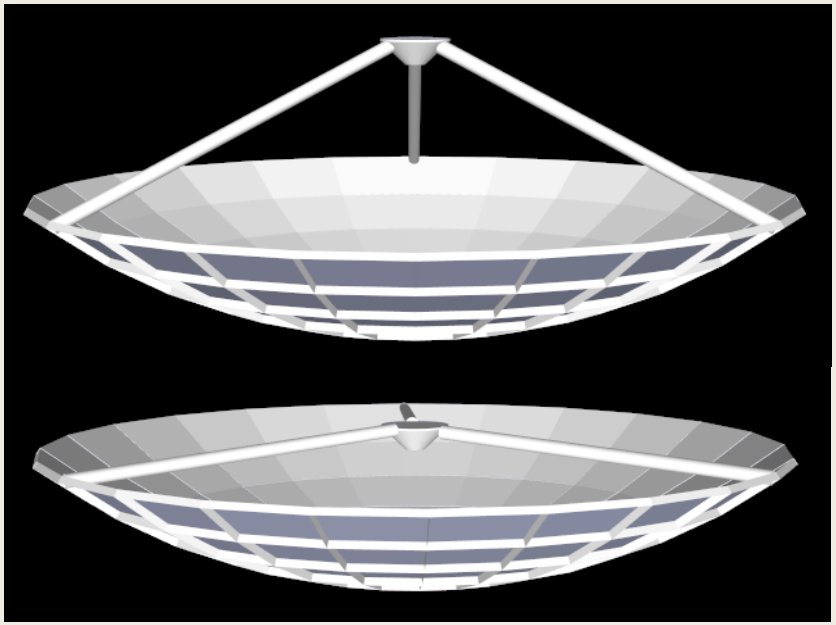
The TSSM in-situ probe instrument area and volume allocations (left), and the corresponding allocations in TABS (right). Pictures are not scaled equal

* TSSM In Situ Elements, ESA contribution to the Titan Saturn System Mission, ESA-SRE(2008)4, 12 February 2009.

Communications

- The sizing of the HGA antenna is critical in understanding the volume that constrains the entry probe and aeroshell.

Parabolic Dish: Diameter = 100cm; Focal Point = 36.8cm; Depth = 17cm

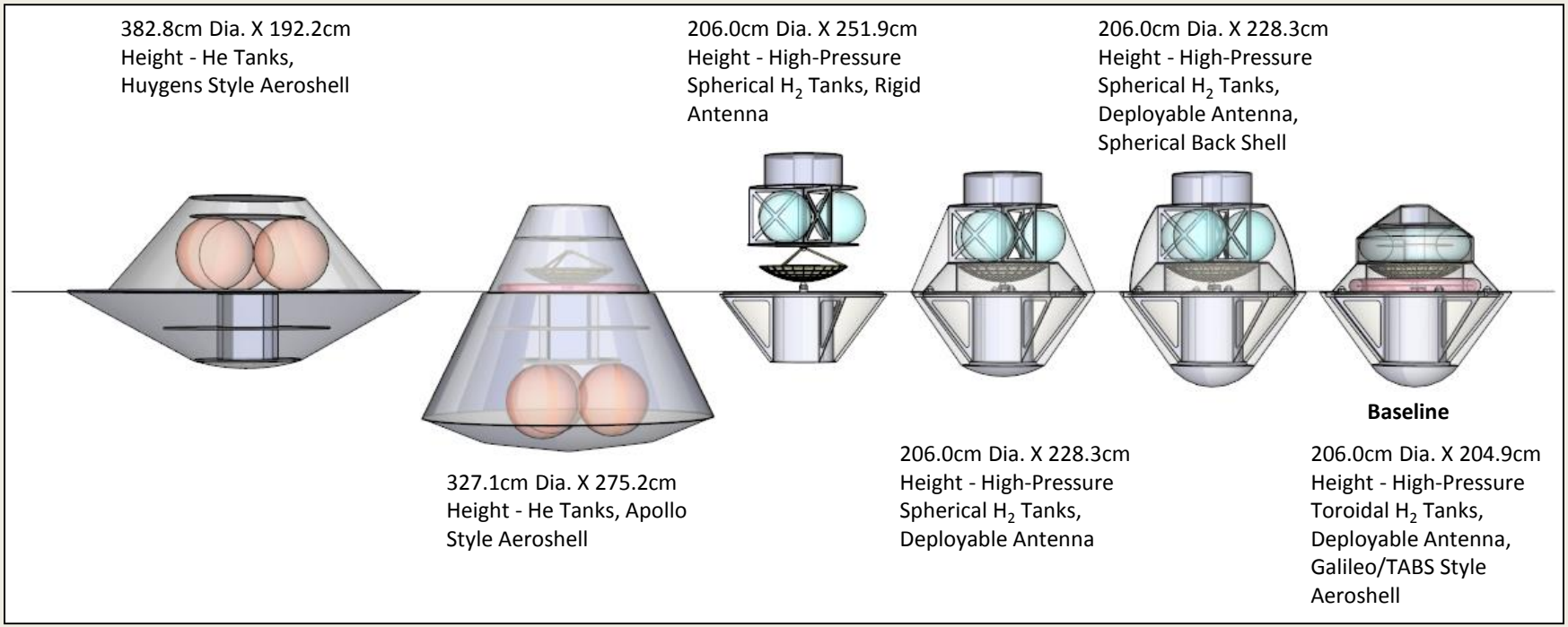


	DTE Downlink
Transmit System	
Antenna Type	Parabolic Reflector
Frequency (GHz) / Band	35 / Ka
Antenna Diam / Length (cm)	100
RF Output Power (W)	25
Antenna Efficiency	0.6
Effective Antenna Area (m2)	0.471
Antenna Gain (dB)	49.1
Link Characteristics	
Slant Range (km)	1.583E+09
Incidental Losses (dB)	1
Free Space Loss (dB)	307.3
Receiver Signal-to-Noise Ratio (dB)	14.1
Link Rate (kbps)	19

Good

H_2 Tank Trades and Choice

- Due to packaging constraints and the need to fit all components, including the tanks, within a reasonably sized aeroshell, a toroidal geometry was chosen for the H_2 tank.

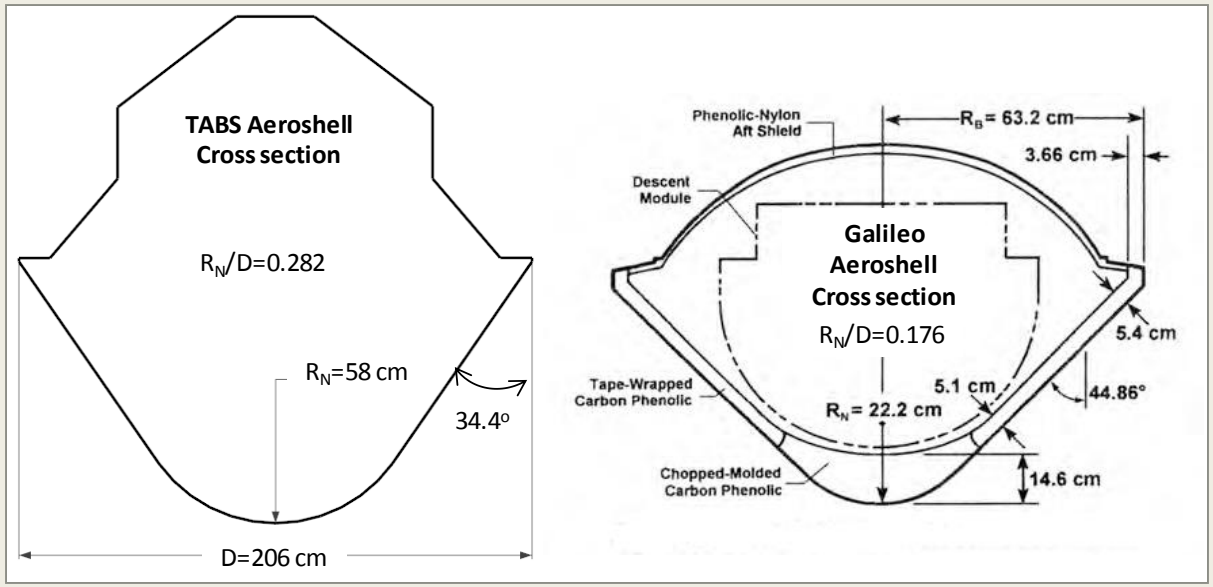


Aeroshell Design Approach

- Once the payload volume, antenna size, and tank volume were established, the overall aeroshell shape and dimensions could be defined.
- A sphere-cone was deemed the most appropriate design option. These designs offer enough experimental data on performance, and lend themselves to analytical tools to estimate aero-thermodynamic properties.
- The actual sphere radius and cone angles were henceforth iteratively derived based on results from the aerothermodynamic computations: a balance of entry deceleration and heat loads.

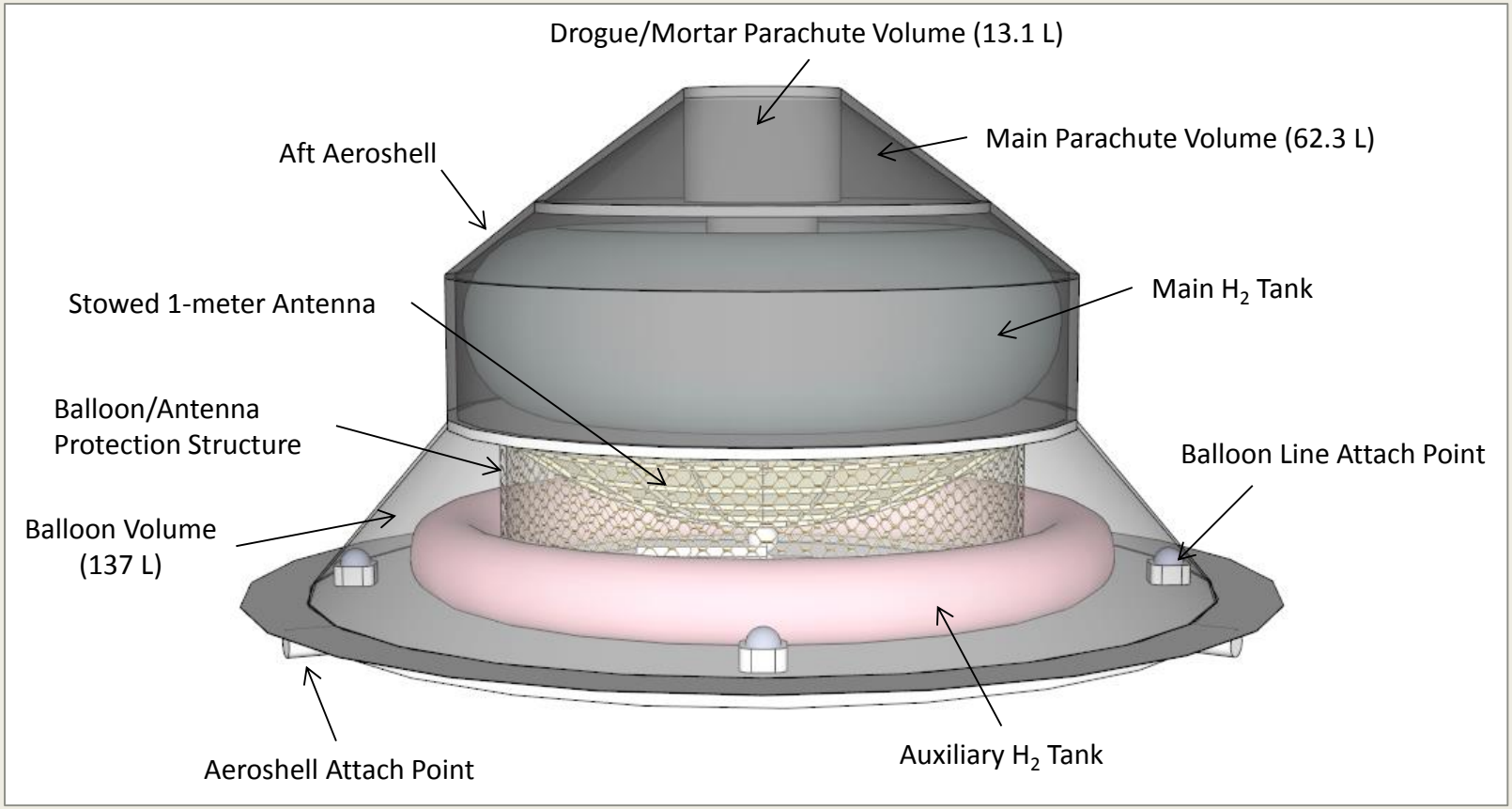
Aeroshell Geometry and Size

- TABS features a medium semi-apex angle of 34.4°, and a spherical nose radius of 0.58m. With a diameter of 2.06m, the *bluntness ratio* (nose radius / diameter) is 0.28, similar to Galileo (0.176) and Mars Pathfinder (0.25).

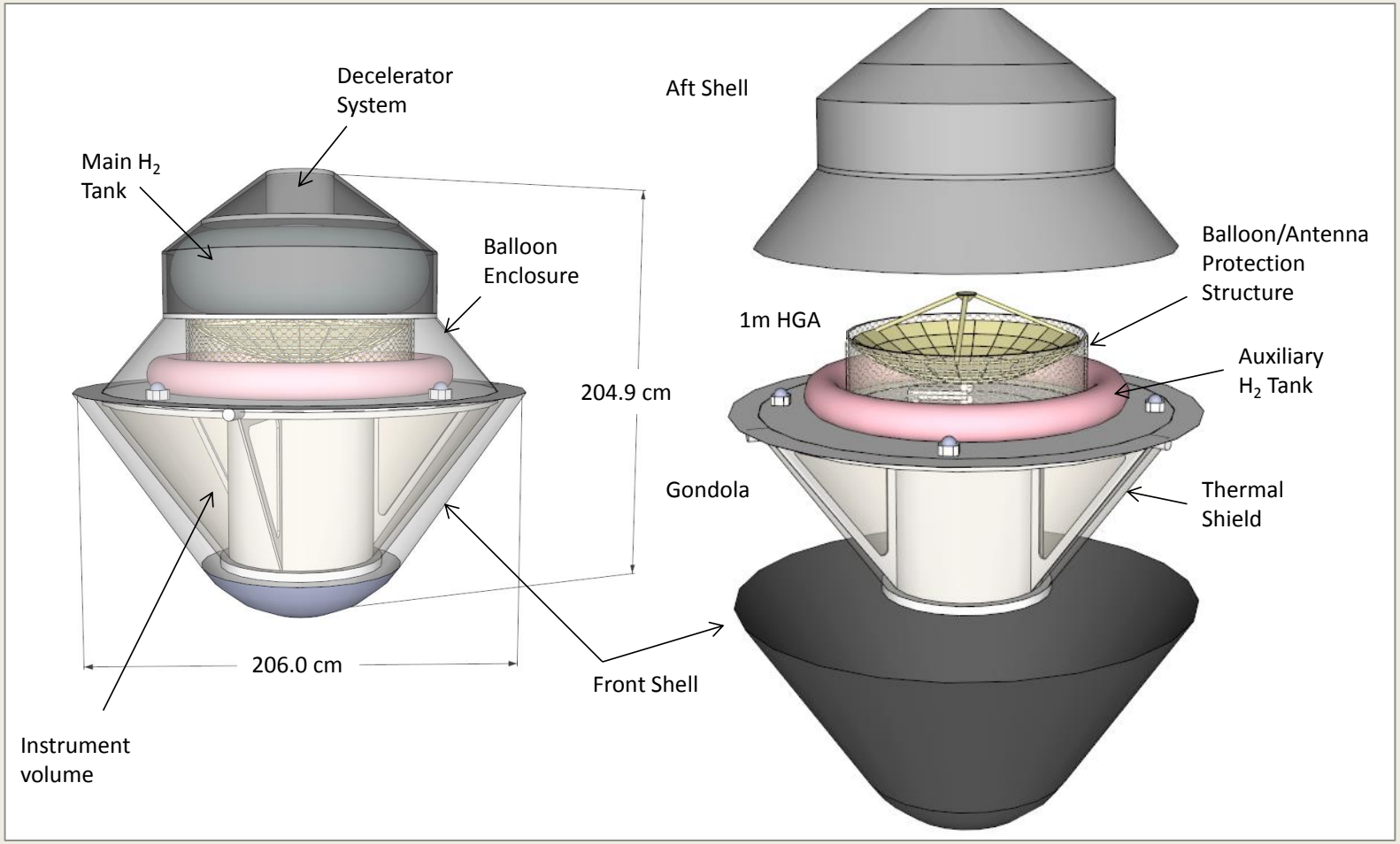


TABS Galileo

Aft Component Accommodation



Probe Layout and Overall Dimension



Entry System Mass

- The Current Best Estimate (CBE) is 483 kg, or 628 kg if a 30% contingency is included. This latter number will be input in the aerothermodynamic computations.
- The mass together with the aeroshell geometry specifies the system input parameters needed to estimate the entry aerodynamic and the thermal loads.

Component	Select Mass (kg)
	Totals
Forward Ballast	40.52
Aeroshell	
Subtotal	201.76
Gondola	
Subtotal	35.87
Main Tank Support Structure	
Subtotal	9.85
Drogue and Parachute Container	
Subtotal	4.13
Total Structure and Entry System	292.13
Buoyant Gas System	99.00
Science Instruments	17.88
Bus Components	52.45
Parachute System	21.68
Total Entry System CBE	483.14
Contingency	144.94
Total Entry System	628.08

Aerodynamics

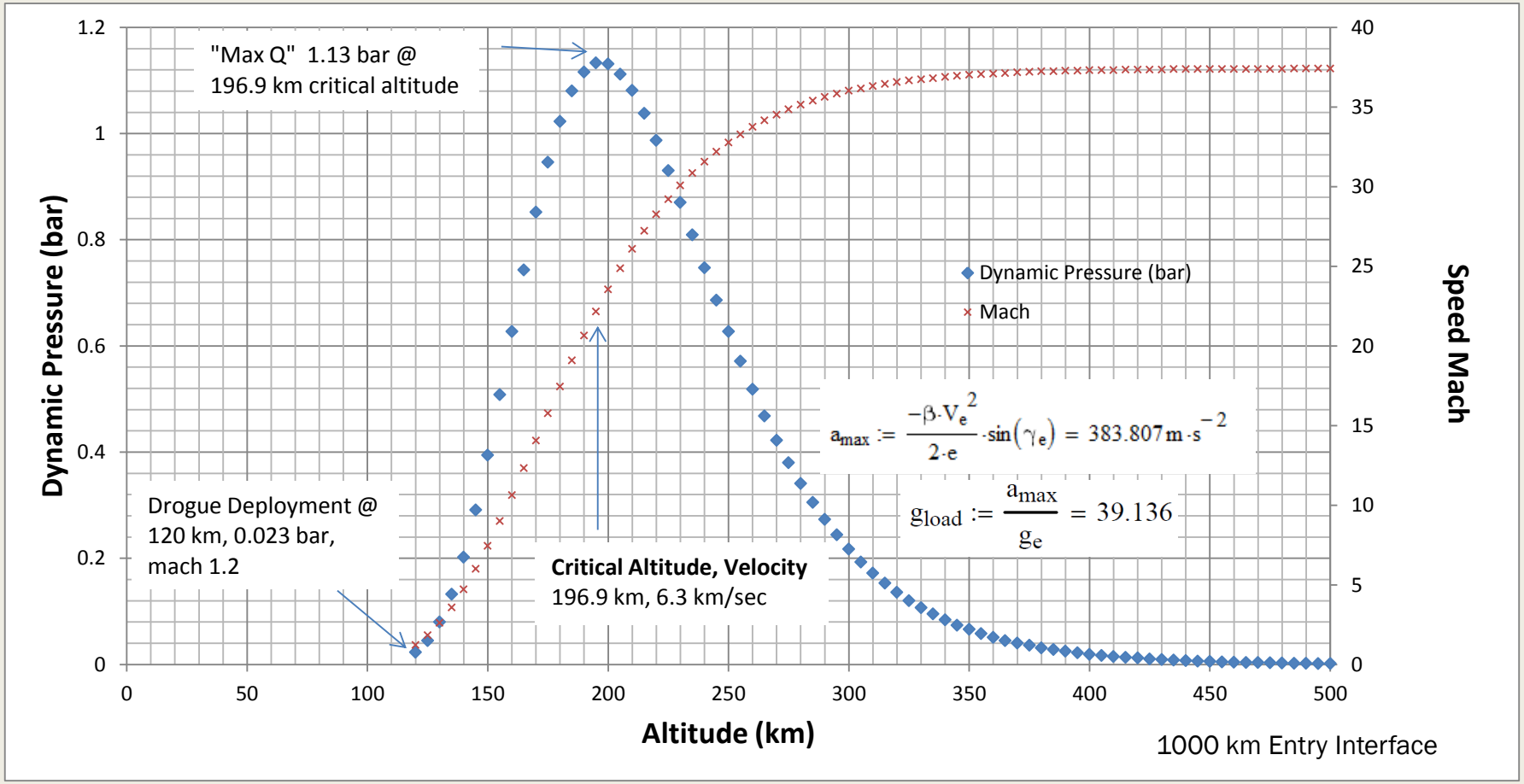
- Titan's normalized atmospheric composition for major elements (mixing ratios), at 981 km is ≈
  - *N_2 = 0.984, CH_4 = 0.0131, H_2 = 0.0033 (N_2 ≈ 0.78 for Earth)*
- The atmospheric scale height is the vertical distance over which the density and pressure fall by a factor of *1/e*. For the ballistic corridor of interest it is ≈ $\frac{1}{\beta} = 40.007 \cdot \mathrm{km}$
- The exponential atmospheric model approximation for Titan at ballistic flight altitudes (>/ ≈ 40 to 120 km) is

$$\rho_{mod}(h) := \rho_0 \cdot e^{-\beta \cdot h}$$

where $\rho_0 := 0.7763 \frac{kg}{m^3}$ And h = height above surface

Aerodynamics

First-order ballistic entry analysis

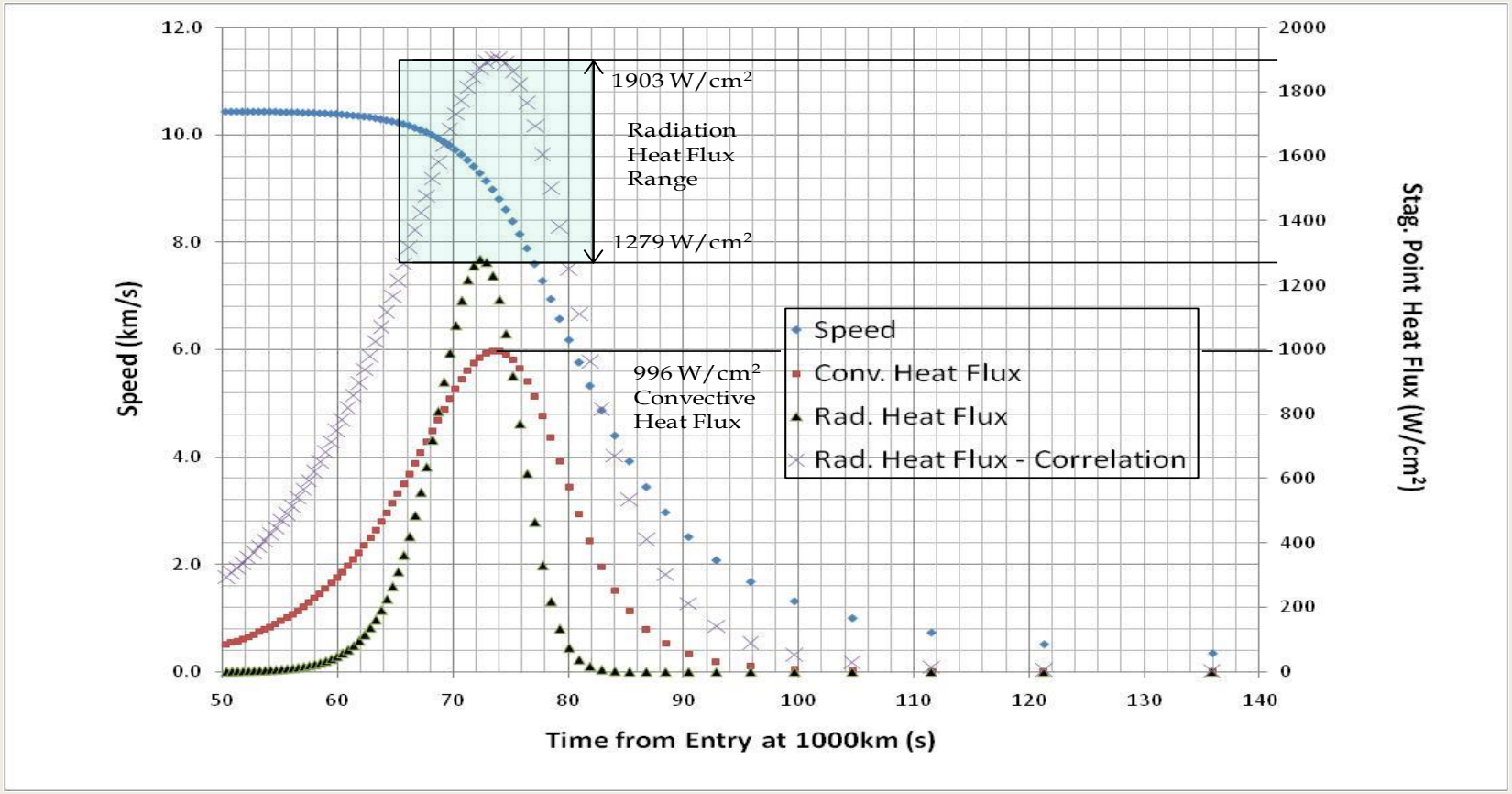


$A_s := 3.33m^2$ $\quad C_D = 0.638$ $\quad C_B := \frac{m_{sn}}{A_s \cdot C_D} = 295.457 \cdot \frac{kg}{m^2}$ $\quad \gamma_e := -50.0deg$ $\quad V_e := 10.439 \frac{km}{s}$

Aerothermodynamics

- The thermal loads on the entry vehicle significantly affect its design, including the selection of an appropriate TPS.
- The *total heat load* will result in an overall increase in the vehicle temperature.
- The *instantaneous heating rate*, being local or body average, affects the thermal gradients across the vehicle, and hence can significantly result in differential expansion and mechanical stresses of the structural components.
- The maximum local heating rate occurs at the leading edge of a blunt body, or at the *stagnation point*.
- **Whereas a shallow, larger trajectory will increase the total heat input, or overall vehicle temperature (longer flight time), a steep trajectory (shorter flight time, greater deceleration and friction) will increase the local heating rate, particularly at the stagnation point.**
- A balance is achieved by adjusting the flight path angle, which in combination with the vehicle geometry and mass, yield a determinate heat input.

Aerothermodynamics



Peak specific heat input (enthalpy)	1.10×10^7 J/kg
Stagnation point Integrated Convective Heat Flux	1.91×10^4 J/cm^2
Stagnation point Integrated Radiative Heat Flux	4.42×10^4 J/cm^2
Total Stagnation Point Integrated Heat Flux	6.33×10^4 J/cm^2
Maximum Heat Shield Thickness (stagnation point)	1.648 cm

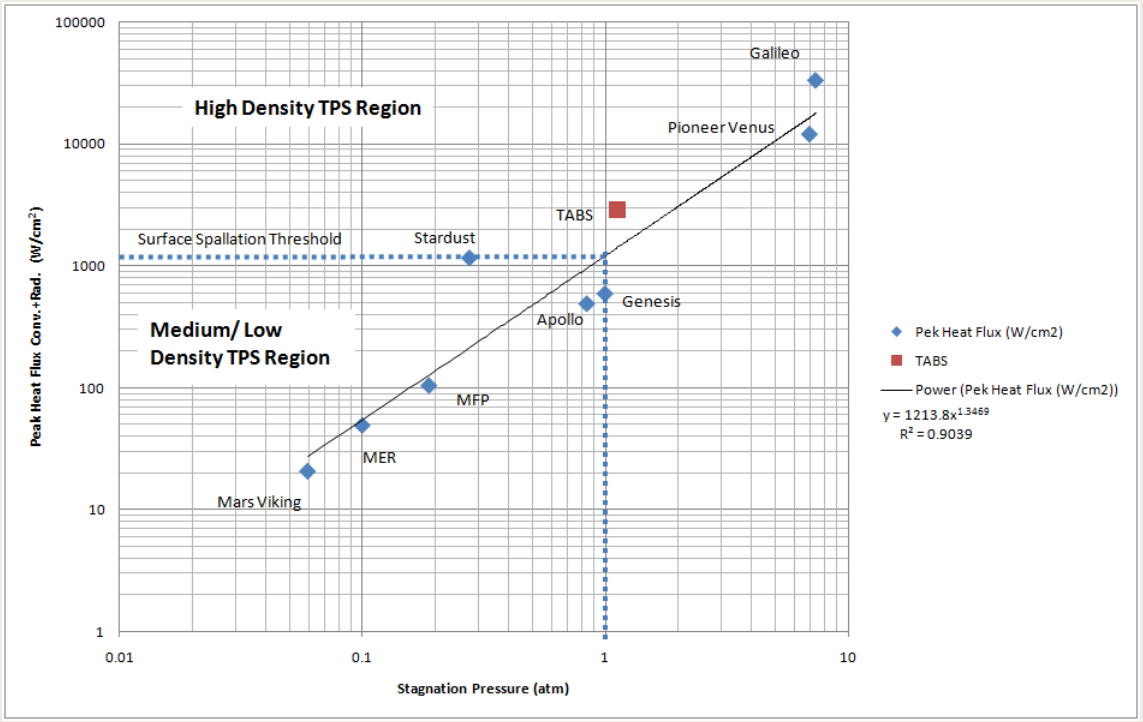
Aero-thermo-dynamic Model Validation - Huygens

- Model compares well against more sophisticated analysis, and is appropriate for preliminary design.

BALLISTIC ENTRY AEROTHERMODYNAMIC ANALYSIS	EM Model / Huygens	Huygens
Aerodynamics		
Max. Deceleration G-Load	15.4	12.4
Velocity at Max G (km/s)	3.7	3.5
Critical Altitude (km)	273	246
Maximum Stagnation Point Dynamic Pressure (atm)	0.1	0.1
Drogue Deployment Mach No.	1.4	1.4
Flight Time From Entry Interface to Drogue Deployment (s)	184	203
Aerothermodynamics		
Stagnation Point Heating - Convective		
Max. Stagnation Point Heating Rate (W/cm^2)	46	46
Stagnation Point Heating - Radiative		
Max. Stagnation Point Heating Rate (W/cm^2)	185	150
Peak Heat Loads at the Stagnation Point (Conv. + Rad.)		
Maximum Heating Rate (W/cm^2)	232	196
Maximum Integrated Heat Flux (J/cm^2)	8.9E+03	4.20E+03

Thermal Protection System (TPS)

- The TPS material choice must be such that the total heat into the vehicle is dissipated effectively in order to avoid structural failure.
- Typically an ablator is characterized by its density. The higher the density, the greatest its strength but also its thermal conductivity.
- Since thermal conductivity increases with density, so does the likelihood of Char "spallation". Spallation is to be avoided, as it consumes material with inefficient removal of heat.



- Ablative TPS material density requirements can be inferred from the expected pressure and peak heat flux at the stagnation point. *
- Assuming a total integrated convective and radiative heat flux at the stagnation point during the flight of ≈ 63 KJ/cm^2, a TPS density of 1.45 gm/cm^3, and a TPS heat of ablation of 26.5MJ/kg:
- A conservative heat shield (recession) thickness is about 1.6 cm.

* Laub, B., and E. Venkatapathy: "Thermal Protection System Technology and Facility Needs for Demanding Future Planetary Missions," International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, Lisbon, Portugal, October 2003.

Resin Impregnated Carbon Ablator (RICA)

- Heritage hyperbolic-entry speed carbon/Phenolic ablators rely on materials that are no longer in production (i.e., Galileo, Pioneer Venus)
- Development of alternatives such as RICA is necessary for future NASA planetary entry and Earth re-entry missions.
- RICA's performance was tested both in Methane to simulate Titan's atmospheric composition, and in air.

Resin-Impregnated Carbon Ablator: A New Ablative Material for Hyperbolic Entry Speeds

From surface temperatures as high as ≈3,000 °C, the measured back temperature is only 50 °C.

Goddard Space Flight Center, Greenbelt, Maryland

Ablative materials are required to protect a space vehicle from the extreme temperatures encountered during the most demanding (hyperbolic) atmospheric entry velocities, either for probes launched toward other celestial bodies, or coming back to Earth from deep space missions. To that effect, the resin-impregnated carbon ablator (RICA) is a high-temperature carbon/phenolic ablative thermal protection system (TPS) material designed to use modern and commercially viable components in its manufacture. Heritage carbon/phenolic ablators intended for this use rely on materials that are no longer in production (i.e., Galileo, Pioneer Venus); hence the development of alternatives such as RICA is necessary for future NASA planetary entry and Earth re-entry missions. RICA's capabilities were initially measured in air for Earth re-entry applications, where it was exposed to a heat

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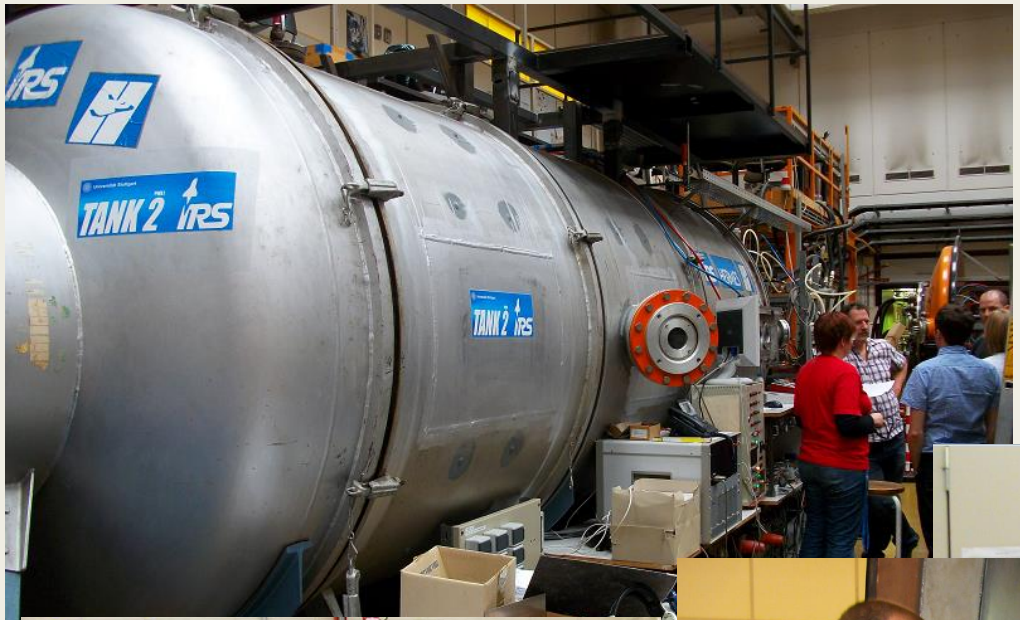
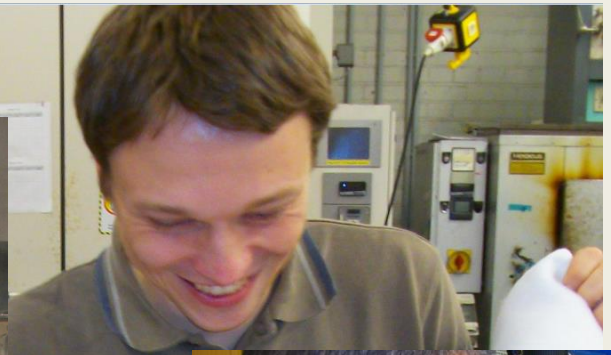
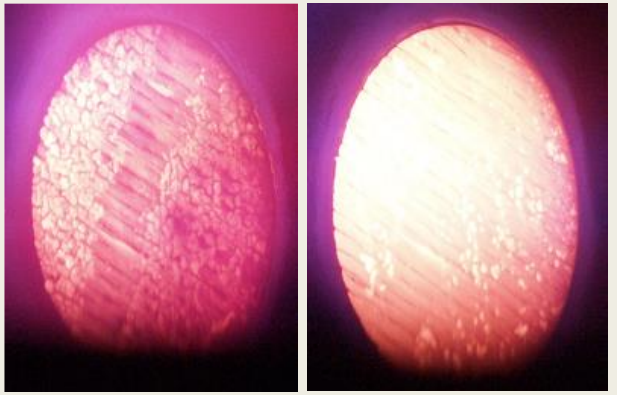
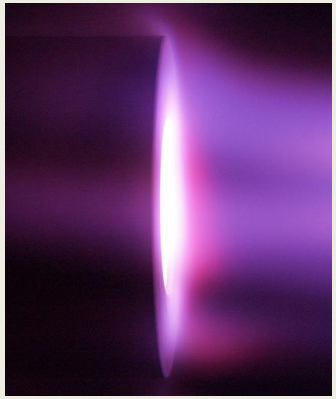
TPS Testing – Universität Stuttgart



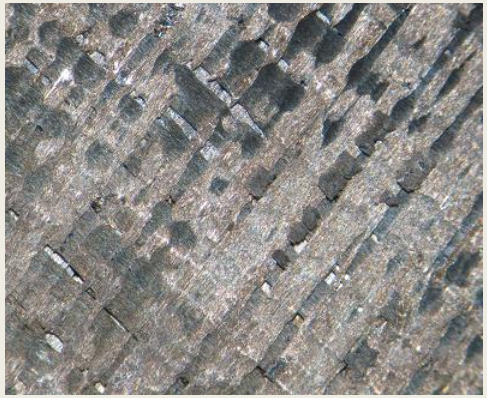


RICA Test Results





RICA Sample during Plasma Wind Tunnel Testing



Typical RICA material surface condition after test

RICA-5B, 3B, 3A and 5A have proven viable. RICA-XC materials are not considered viable.

RICA	Phenolic Content (~%)	Carbon Content (~%)	Density (gm/mL)	Plasma Wind Tunnel Heat Flux (MW/m^2)	Heat Duration (s)	Integrated Heat Input (J/m^2)	Mass Loss (gm)	Average Recession (mm)	Average Surface Temp from Pyrometer (C)	Average Thermal Gradient (K/mm)	Heat of Ablation (J/kg)
5C	17	83	1.41	1.4	478	6.69E+08	7.84	4.218	1978.1	44.37	4.9E+07
5A (1)	27	73	1.39	14	22	3.08E+08	3.33	1.96	3336.1	34.32	1.1E+08
3A	24	76	1.36	1.4	478	6.69E+08	3.32	0.342	1962.5	54.50	8.5E+07
5B	33	67	1.37	1.4	476	6.67E+08	3.73	1.217	1990.8	53.68	7.7E+07
3B	31	69	1.35	1.4	477	6.67E+08	3.70	1.143	1967.5	51.11	8.5E+07

(1) Tested in Air; all other tested in Methane

Decelerator System

- The following four requirements must be factored in the design of the decelerator system (both drogue and main parachutes):
  - *Strength: The decelerator must survive deployment forces without damage*
  - *Drag: The drogue parachute drag shall be adjusted to allow for safe deployment at the given speed and dynamic pressures, while minimizing mass. The main parachute must reduce the descent speed to allow sufficient time for the balloon to inflate. Descent rate must also be slow enough to minimize the relative vertical wind speed (dynamic forces) to acceptable levels for material deployment and inflation*
  - *Volume: The decelerator system must strive to occupy the minimum volume possible, or fit within the volume constrains imposed by the vehicle design*
  - *Stability: The drogue and main parachutes must be stable enough to reduce oscillations that can either affect main deployment after drogue release, or balloon inflation under main parachute.*

Decelerator System

- The maximum parachute structural loads generally occur during inflation, so this point defines its required strength.
- The sudden change in the coefficient of drag (C_d) during deployment creates an almost instantaneous shock impulse of deceleration.
  - *This translates to some G-value: the parachute opening shock.*
- The *probe* drag force at the exact location just prior to parachute release *must be smaller than the shock force of parachute deployment (or its drag force)* if the parachute is to successfully trail behind the probe.

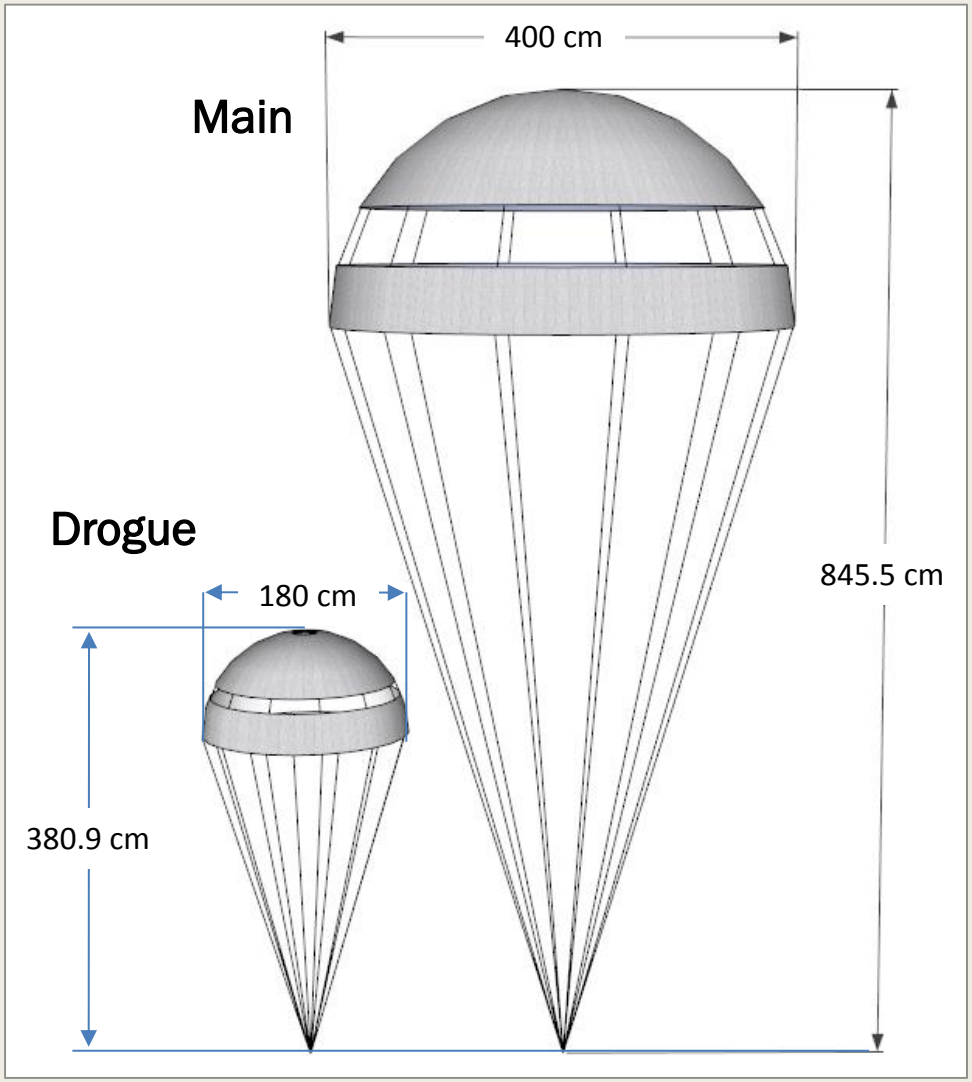
Balloon Inflation and Main Parachute

- The main parachute sizing is inexorably attached to the balloon inflation in that its size must support the orderly and safe deployment of the balloon by a predefined altitude.
- Unlike Huygens, the main parachute in TABS will be released *after* crossing-over through Mach 1. The reason is the need to maintain the back cover to protect the Hydrogen tanks and lines through the transonic phase.
- To properly size the main parachute, its descent rate must be such that complete balloon inflation is achieved by its desired operational altitude, or 10km. More importantly, it must provide a decent rate that minimizes dynamic loads on the balloon material as it inflates. The descent rate is set to be in the neighborhood of 5 to 10 m/s.

Decelerator System – Disk-Gap-Band (DGB)

The following variables affect the performance parameters as given below in the proportionality indicated (direct or inverse):

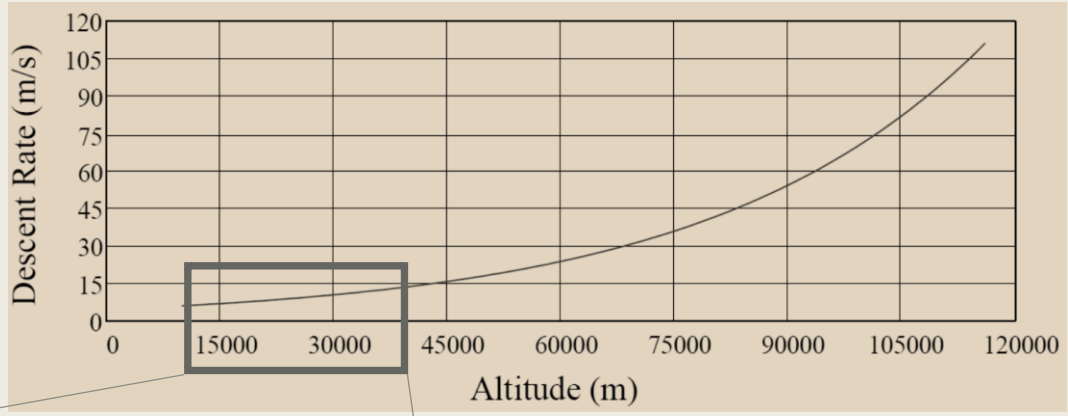
1. *Diameter* affects *drag* (direct) and packing *volume* (direct).
2. *Band Width* affects *stability* (direct), *drag* (inverse), *volume* (direct).
3. *Material Thickness* affects *strength* (direct) and pack *volume* (direct).

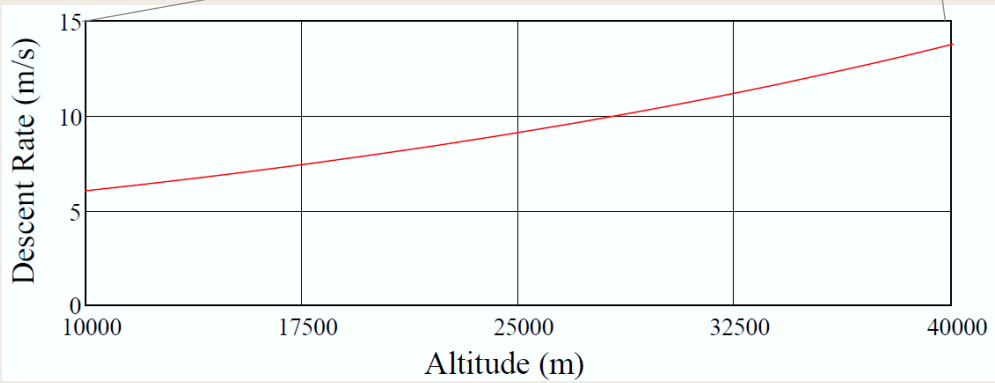


Descent Rate and Balloon Inflation

- The terminal velocity (or descent rate) under the main is approximated by:

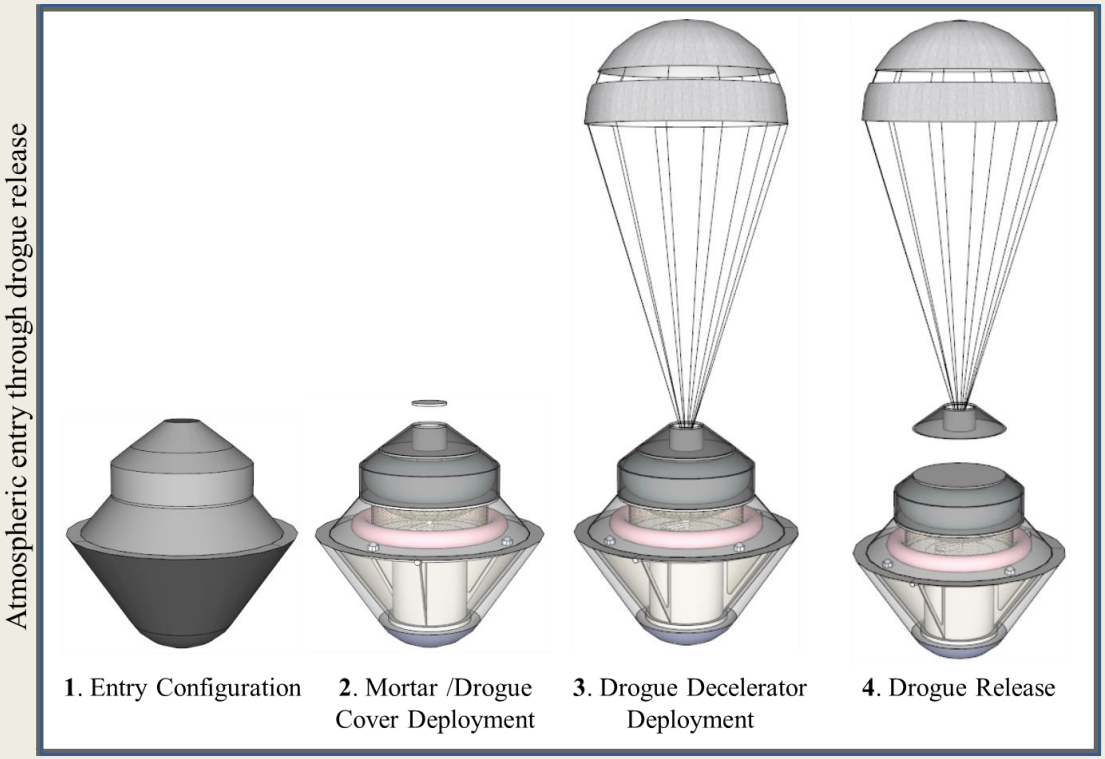
$$V_{tpx}(h_t) := \sqrt{\frac{2 \cdot m_{sn} \cdot g_n}{C_{Dp} \cdot \rho_{m120}(h_t) \cdot S_p}}$$





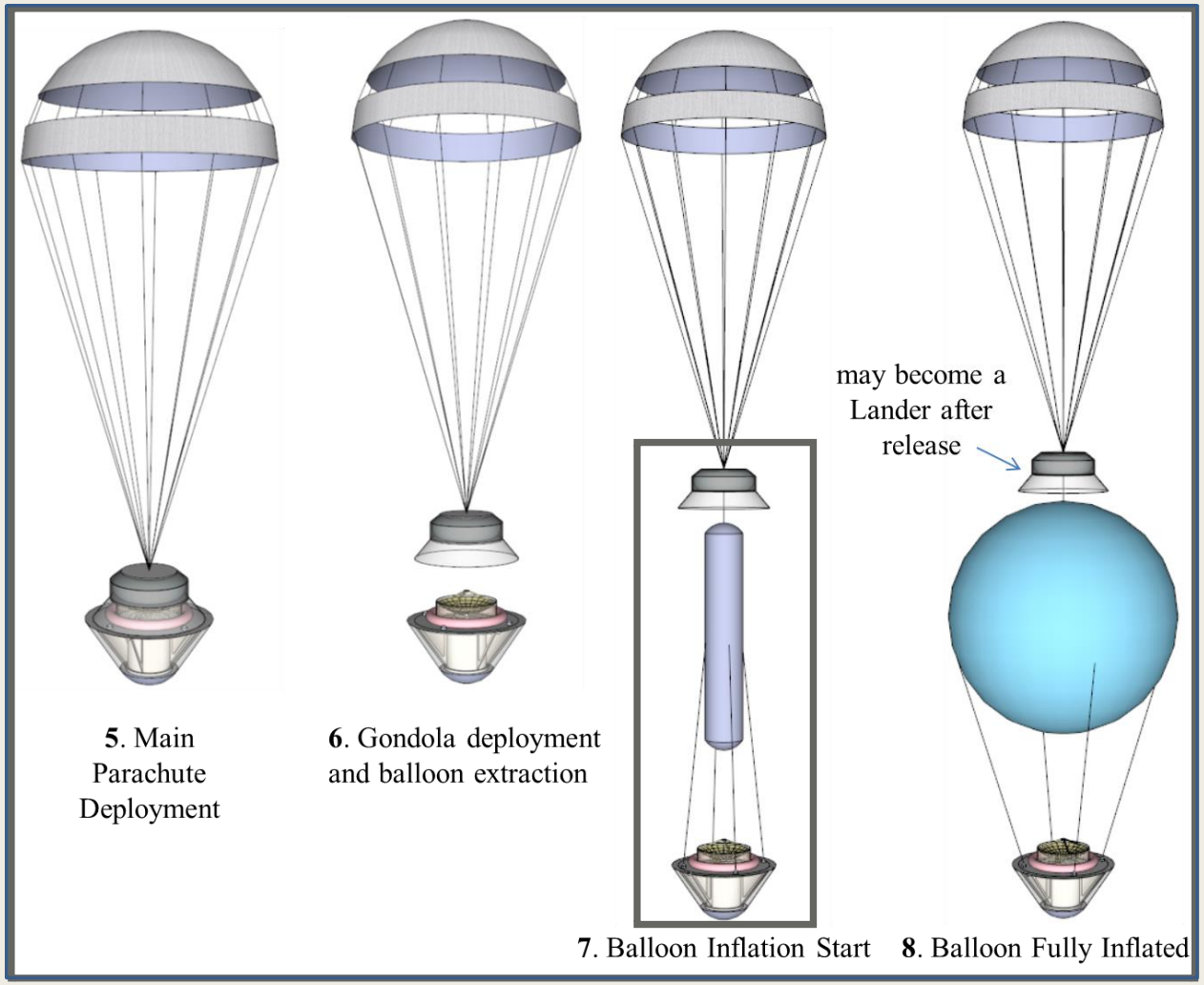
As can be seen, the descent rate below ~37 km is nearly constant. Also, at ~28 km the rate drops below 10 m/s. We choose this as the balloon inflation start altitude. Balloon is fully inflated at ~14km altitude.

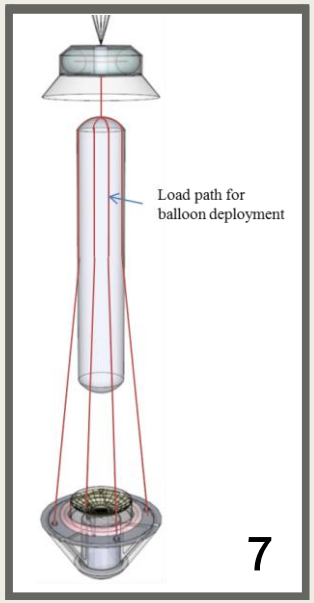
Deployment Sequence - Concept



Deployment Sequence - Concept

Main parachute deployment through balloon inflation

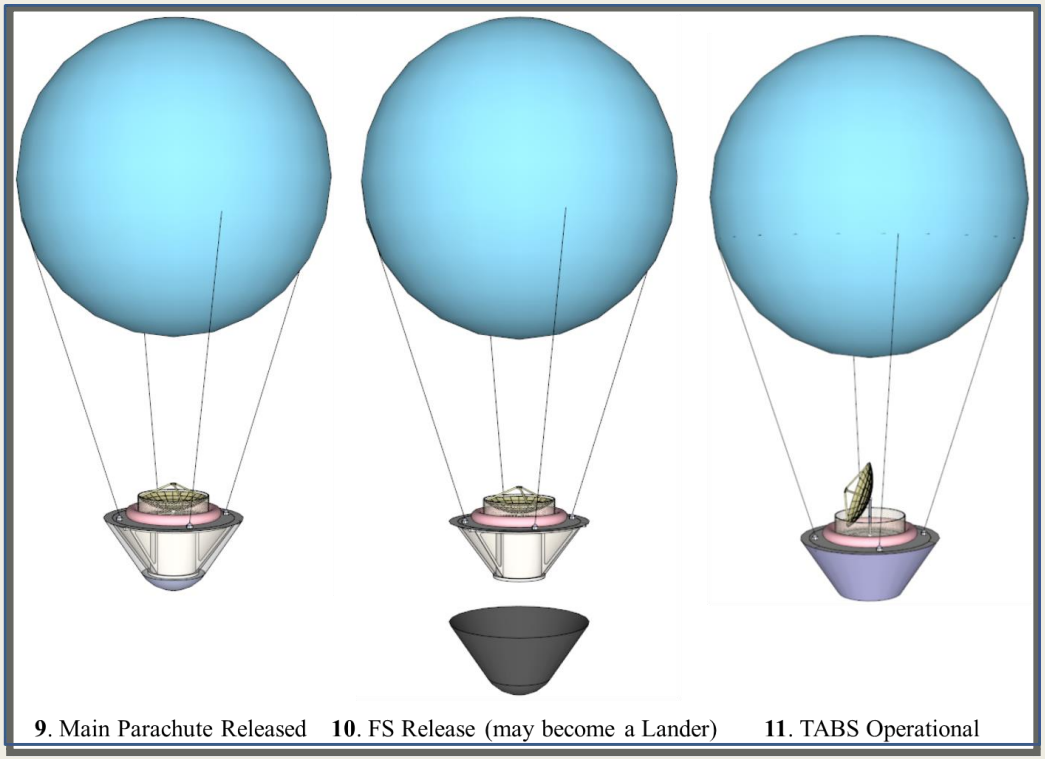




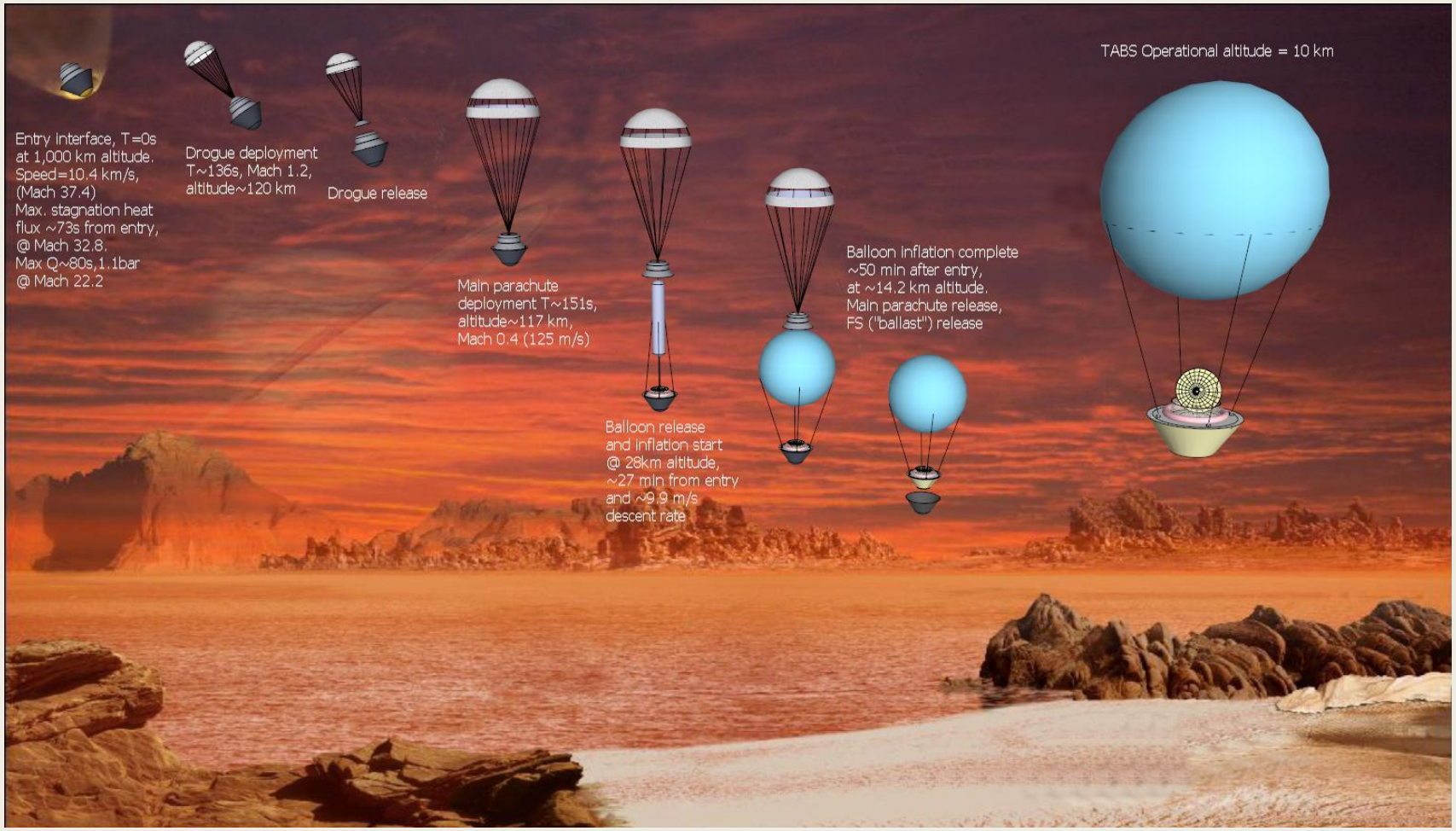
In order to ensure the deployment loads are not unduly carried by the fabric, reinforced material is used to connect the balloon lines during initial drop-off and opening. Inflation will then occur after the system is fully extended. This load path is illustrated above.

Deployment Sequence - Concept

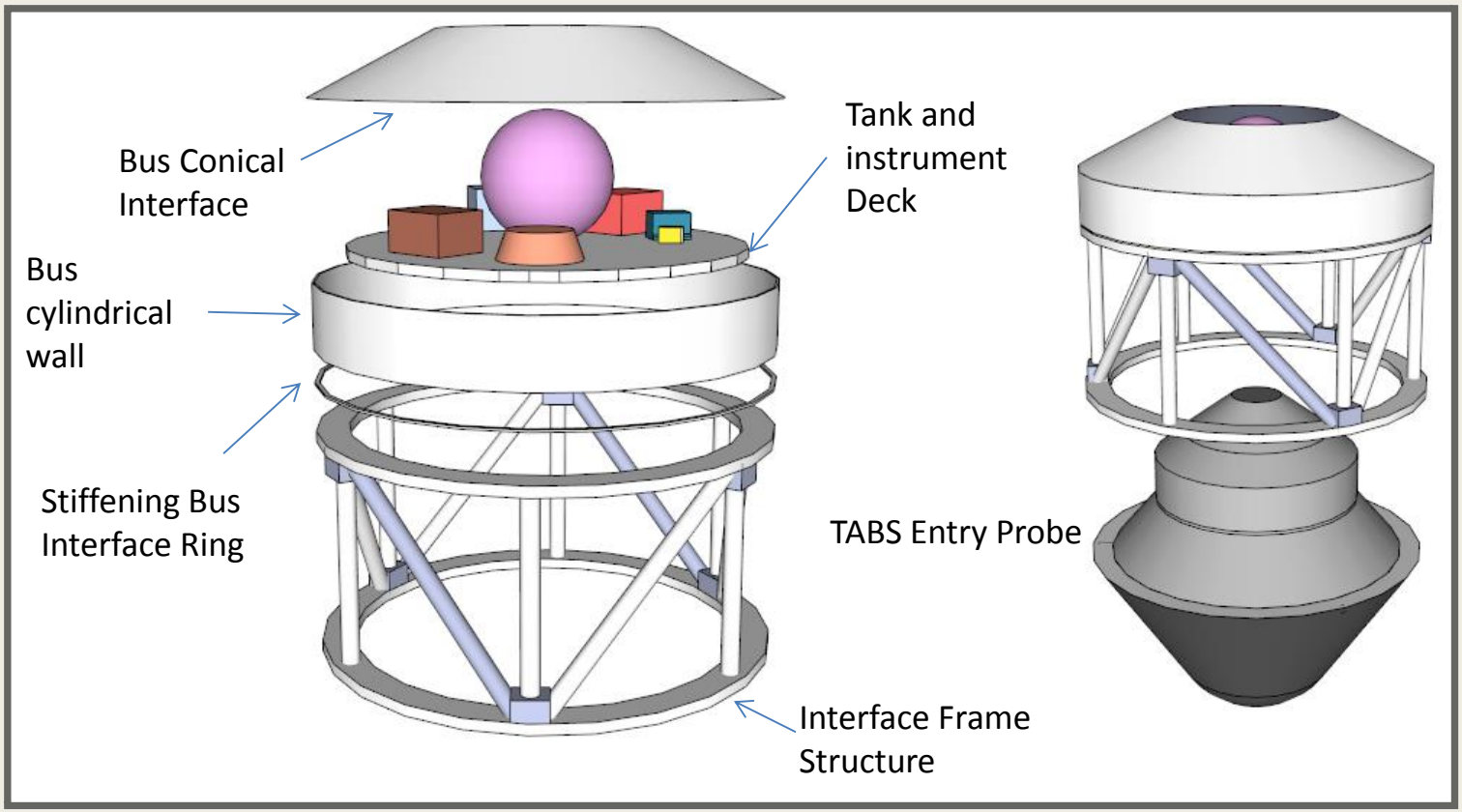
Main parachute release through science operations



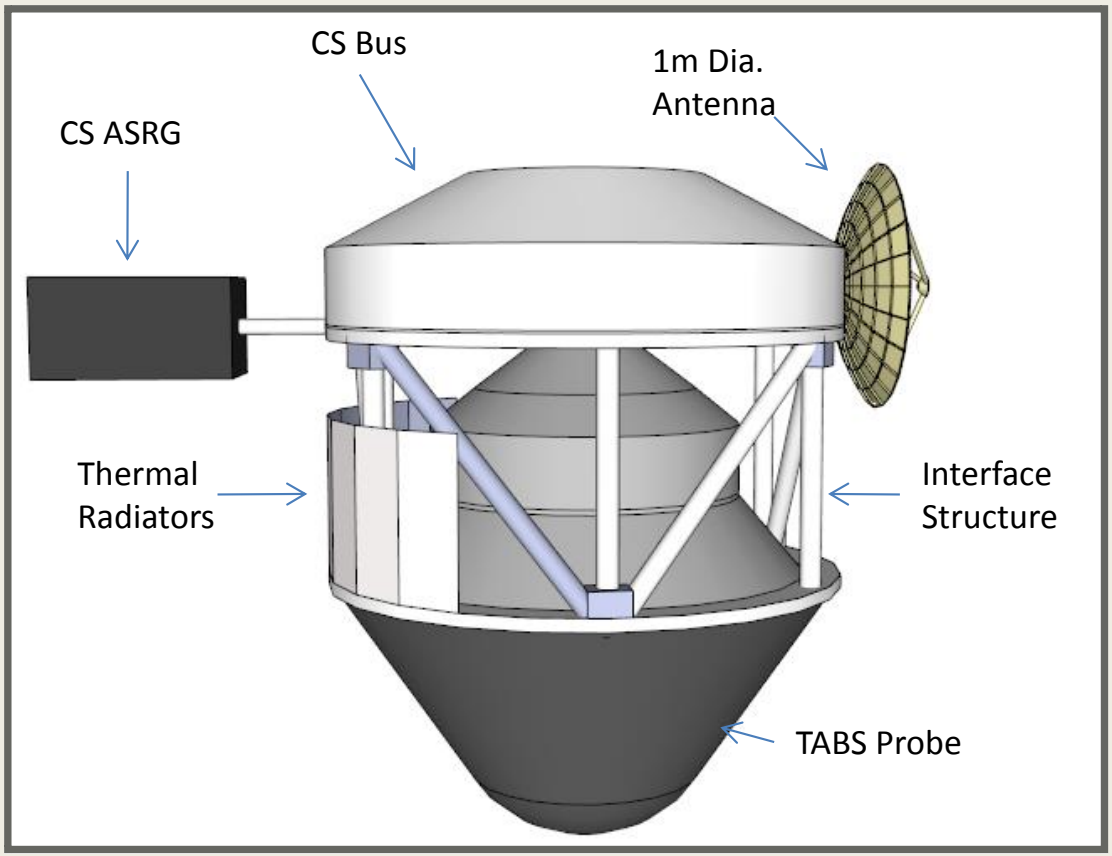
Deployment Timeline and Operational Configuration



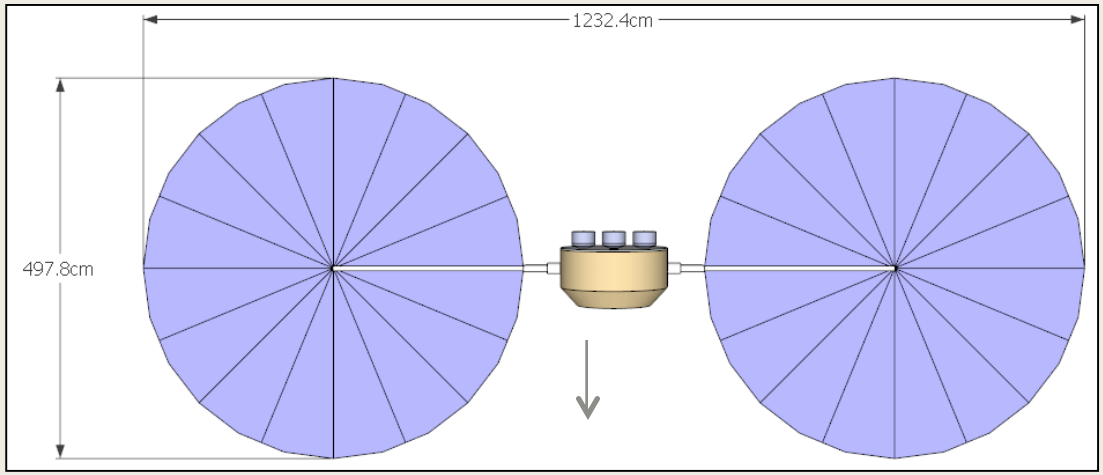
TABS interface and carrier spacecraft structures

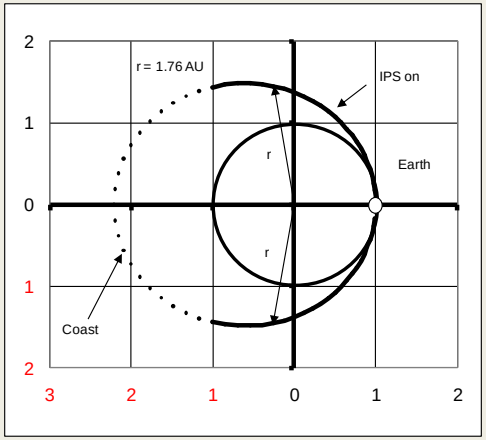


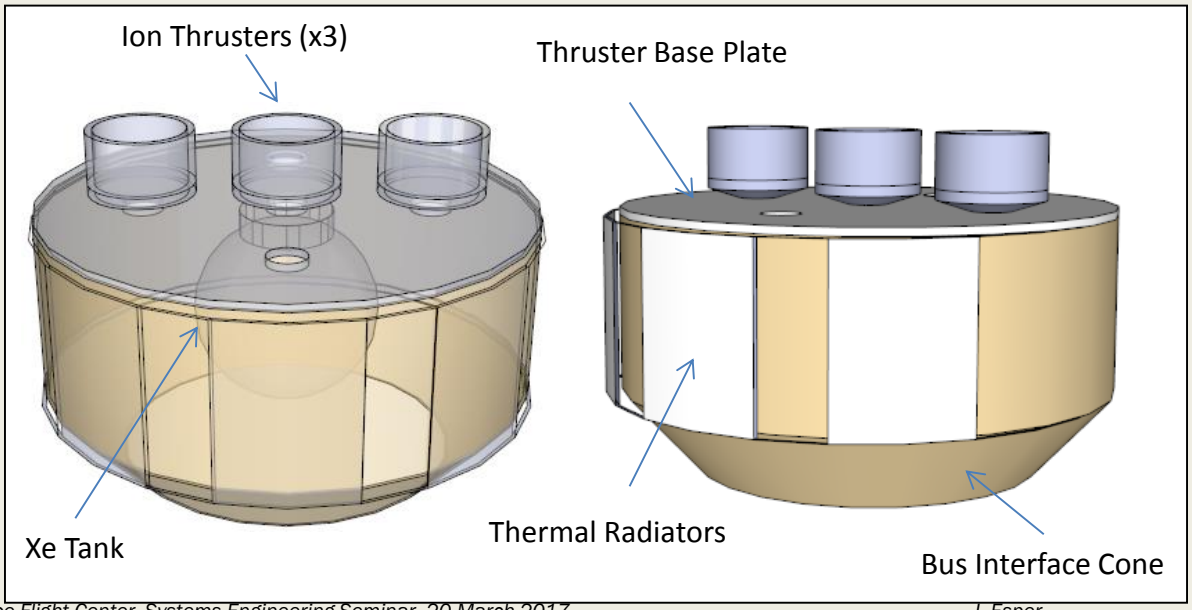
CS Power and communications subsystems



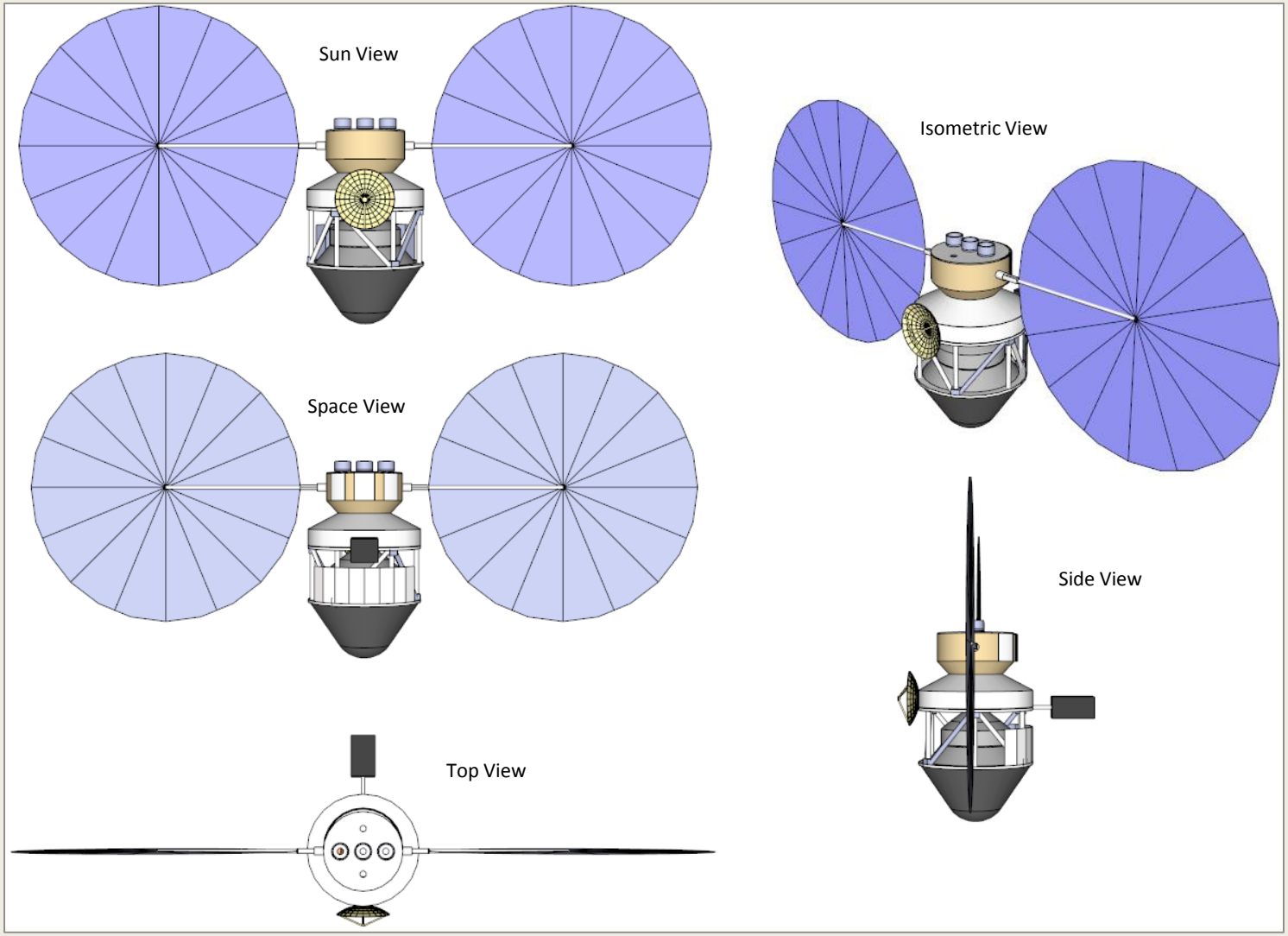
Solar Electric Propulsion Module



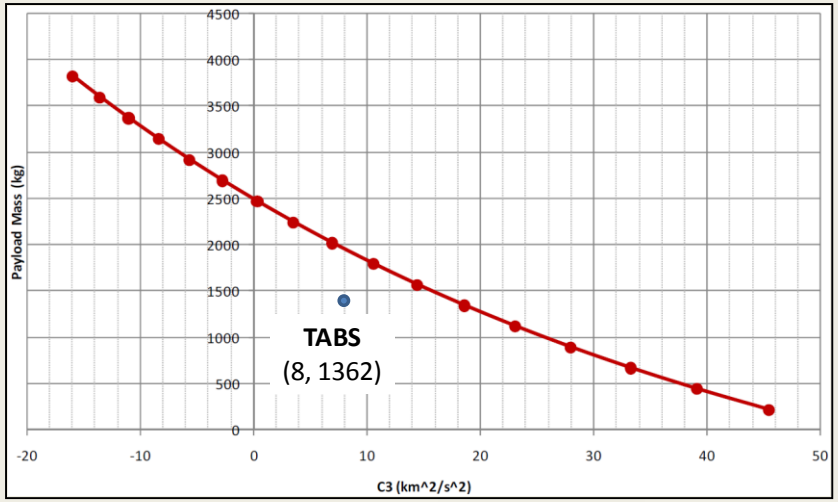




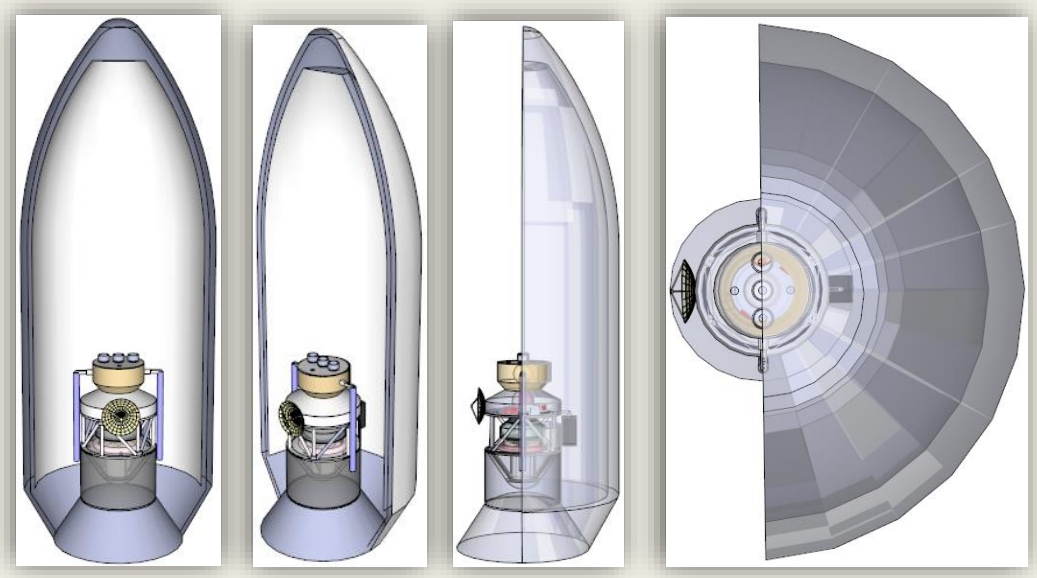
Integrated Space System



TABS system and the Falcon 9



Total Spacecraft Injected Mass (w/o Contingency)	***1047.9***
Total Spacecraft Injected Mass (Incl. 30% Contingency)	***1362.3***
Launch Vehicle Injected Mass Capability (Falcon 9)	1950
Launch Vehicle Margin	587.7
Launch Vehicle Margin Percent	30%



Conclusions and Future Prospect

- A focused, mission design concept to visit Titan was developed.
- A ***feasible alternative to a Titan Montgolfier was developed.***
- Provided an ***empirical contribution to the field of hyperbolic entry ablator research, with direct application to Titan.***
- Through allocation of ample contingencies and margin, the TABS mission design has ***left the door open for international cooperation*** in an area where pooling institutional and national resources can prove beneficial.

Titan is the only body in the solar system where liquid oceans exist. It has a Nitrogen-rich atmosphere where pre-biotic processes may be occurring and organic compounds abound. The existence of life in a form we yet do not understand cannot be ruled out, if hydrocarbon solvents were to replace water as the "soup of life": so **why are we not going there?**

Dedication

This presentation is dedicated to the memory of Prof. Dr. Hans-Peter Röser, for his influence and inspiration in my study and development of planetary entry systems.

And to Dr. Alfredo Esper, who instilled in me a sense of awe for nature and always encouraged me to reach for the stars (thanks Papa).

Dr. Alfredo Esper
1923 - 2005

Prof. Dr. Hans-Peter Röser
1949 - 2015