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TITAN AEROCAPTURE MISSION AND SPACECRAFT DESIGN OVERVIEW

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ABSTRACT

A detailed Titan aerocapture systems analysis and spacecraft design study was performed as part of NASA's In-Space Propulsion Program. The primary objective was to engineer a point design based on blunt body aeroshell technology and quantitatively assess feasibility and performance. This paper provides an overview of the mission and spacecraft design resulting from that study and references other papers that provide further details on critical subsystems. It also reviews the science requirements underlying the selected mission concept of an aerocaptured orbiter and a separate entry vehicle that delivers an aerobot into the Titan atmosphere. Including aeroshells and 30% contingencies, the estimated mass of the orbiter is ~1100 kg and that of the entry vehicle ~360 kg. Solar electric propulsion (SEP) and an Earth gravity assist is used to get the tandem vehicle to Titan in 6.5 years, with orbiter – entry vehicle separation occurring one month prior to arrival. The SEP module, orbiter and entry vehicle are vertically stacked on a medium class launch vehicle and connected with a truss structure. Power profiles based on a strawman instrument suite and telecom strategy are accommodated with a pair of 120 W (electric) radioisotope thermoelectric generators. Details on the configuration layout, mass and power breakdowns, key design trades and outstanding design issues are also included.

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1. INTRODUCTION

As part of NASA's In-Space Propulsion Program, aerocapture is being investigated as a means for interplanetary orbit insertion. A systems analysis and spacecraft point design study was performed in the Fiscal Year 2002 time frame based on a reference mission to Saturn's moon Titan. The purpose of this study was to quantify the feasibility and performance of an aerocapture system to insert a spacecraft into a science orbit about Titan. This paper provides an overview of the mission and spacecraft design resulting from that study and references other papers presented at this conference that provide further details on mission design, navigation, critical subsystems and the aerothermal environment for aerocapture at Titan.

The overall mission concept includes the delivery of a long duration atmospheric probe to Titan's atmosphere and the use of a Solar Electric Propulsion (SEP) stage for the Earth to Saturn transit. The mission concept is shown to be feasible at the level of detail applied for this study. Many different technical areas and trades consistent with continued Phase A/B efforts are defined at the end of this paper.

2. SCIENCE

2.1 Objectives & Measurements

For this study, the primary science objectives were taken from Chyba *et al.*[1] for a post-Cassini / Huygens Titan mission, listed in priority order:

1. Distribution and composition of organics
2. Organic chemical processes, their chemical context and energy sources
3. Prebiological or protobiological chemistry
4. Geological and geophysical processes and evolution
5. Atmospheric dynamics and meteorology
6. Seasonal variations and interactions of the atmosphere and surface (not addressed in a mission of short lifetime)

These objectives will likely be revisited when results are available from the Cassini / Huygens

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mission. Tamppari *et al.*[2] involved the Titan science community in a workshop that prioritized measurement objectives for such a mission. The highest priorities were determined to be:

1. Global surface morphology
2. Global gross surface composition and chemistry
3. Atmospheric composition and its spatial and temporal variability
4. Atmospheric structure and its spatial and temporal variability: vertical profiles of density, pressure, and temperature
5. Atmospheric dynamics (winds) and meteorology

An independent external review performed after the completion of this study judged these objectives to be appropriate.

2.2 Science Instruments

Table 1 presents the instrument suite selected and the flowdown from science and measurement objectives to the instruments. Although these instruments may be realistic, for the purpose of this study they serve as mass, power, and data volume placeholders for A Titan science payload.

2.2.1 Multi-Spectral Imager

The multi-spectral imager uses spectral coverage in several atmospheric opacity "windows" between 1 and 5 microns to determine surface and atmospheric morphology and chemistry as well as atmospheric dynamics and meteorology. This instrument will fill in any coverage gaps remaining after Cassini / Huygens.

2.2.2 Synthetic Aperture Radar (SAR)

The SAR uses the Orbiter X-Band telecom system with the HGA pointed off-nadir. It makes complementary measurements of surface morphology and meteorology, through clouds that would obscure the imaging instruments' view, and can detect the bottoms of shallow hydrocarbon lakes. Like the imager, it will fill in any coverage gaps remaining after Cassini / Huygens.

2.2.3Microwave Spectrometer

The microwave spectrometer, capable of either nadir- or limb-pointed modes, makes global, low (spatial) resolution measurements of atmospheric structure, dynamics, and meteorology via detailed spectroscopy of emission lines from a few key chemical species. This also yields precise vertical abundance profiles of those species.

2.2.4 Ultrastable Oscillator (USO)

Adding a USO to the Orbiter X-Band telecom system enables atmospheric radio occultation science. Radiometrics obtained when the signal path to Earth passes through Titan's atmosphere allows accurate (1-2%), high-resolution vertical profiling of temperatures and densities at many sites, yielding atmospheric structure and dynamics as well as ionospheric structure

2.3 Atmospheric Probe Science

The Atmospheric Probe (AP) was allocated 5.3 Gbits of total data return; or the capability of the UHF relay link over a one year period. The AP to Orbiter link provides 64 kbps for 30 minutes every 8 days. Although 5.3 Gbits is adequate for general atmospheric and meteorological data (~14 Mbits/day), this volume is likely inadequate for any type of context imaging – this is generally an issue for the AP and not addressed in this study which focuses on the aerocapture technology aspects of the mission.

Table 1. Science Instruments

Instrument	CBE Mass (kg)	CBE Power (W)	Spatial Res (meters)	Point	FOV (deg)	Measure Objective	Science Objective	Total Data Return (Tbits)
Multi-spectral Imager	12	14	~30	Nadir	1.0	1,2,3,5	1,2,3,5	9
Synthetic Aperture Radar	10	30	~200	Off-Nadir	1.15	1,2	4	1.9
Microwave Spectrometer	10	50	N/A	Nadir & Limb	6.5	3,4,5	2,3,5	1.0E-4
Ultra Stable Oscillator	0.8	3	N/A	N/A	N/A	4,5	5	N/A

3. MISSION OVERVIEW

The study was based on a Titan Explorer concept with an Orbiter and an Atmospheric Probe (AP). Certain aspects of the mission were assumed as ground rules from previous studies performed internally at the Jet Propulsion Laboratory's (JPL) Team-X[1,2]. Other aspects of the mission were open to system trades and/or inherited from other outer planet mission studies performed internally at JPL.

3.1 Ground Rules

Several ground rules and assumptions were set to bound the study. These items were not subject to any system trades analysis.

- The mission shall deliver an AP into the Titan atmosphere, and a spacecraft into Titan orbit.
- The total mission lifetime shall be no longer than 10 years.
- The Technology Readiness Level 6 cutoff date shall be no later than Dec 2006.
- The AP will be a "black box" with a 400 kg launch mass allocation.
- The AP operational lifetime will be 1 year.
- The Orbiter shall perform an aerocapture for Titan orbit insertion.
- The Orbiter shall provide global coverage opportunity for all the science instruments.
- Science data return shall utilize no more than 8 hours per day of a 70m ground station.

3.2 Earth to Saturn Trajectory

The Earth to Saturn trajectory, shown in Figure 1, provides a good combination of transit time, Titan entry velocity, launch mass, and SEP propellant/power mass. Many different trajectories were considered which included different launch vehicles, launch dates, transit times, SEP power levels, number of SEP ion engines, and planetary gravity assists. These trajectory options and their associated trades are discussed in detail by Noca, *et al.*[3] The important aspects of the selected trajectory are as follows:

Launch Vehicle:	Delta IV M (4450-14)
Launch C3:	8.6 km^2/sec^2
Launch Mass:	3423 kg (10% reserve)
Launch Date:	Dec 24, 2010
Gravity Assist:	Earth
SEP Burn Time:	30 months, accumulated
SEP Power:	24 kW (End Of Life)
SEP Propellant:	460 kg (no contingency)
Transit Time:	5.9 years
Titan Entry Velocity:	6.5 km/sec

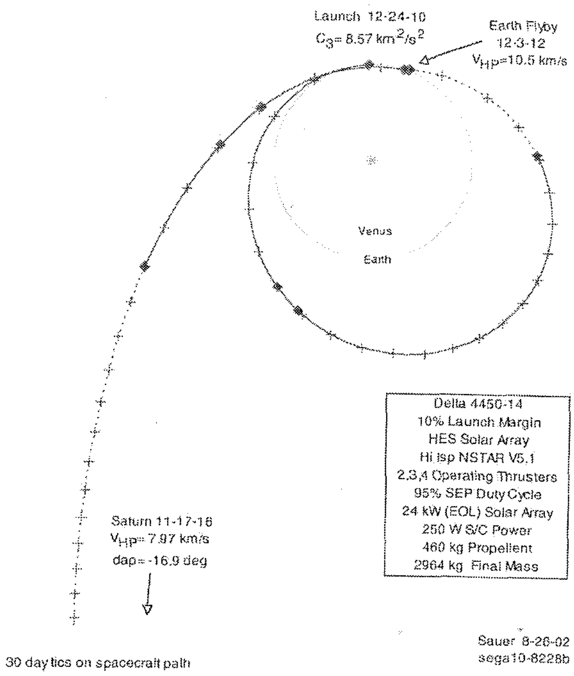

Figure 1. Earth to Saturn SEP trajectory

3.3 Mission Timeline

The mission timeline is listed below. For the "Time" column, 'L' = Launch, 'A' = Orbiter atmospheric interface, 'y' = years, 'd' = days, 'h' = hours, and 'm' = minutes.

Time	Event
L+0	Launch, SEP burn start
L+23m	Earth flyby
L+30m	SEP burn out and jettison at ~2.5 AU
L+5.7y	(A-60d) Traj Correction Maneuver (TCM) 1
A-31d	Probe Release TCM (2)
A-30d	Probe Release
A-29d	Post Release TCM (3)
A-7d	TCM 4
A-1d	TCM 5
A-6h	TCM 6 (if needed)
A-3h	Probe entry
A-1h	Jettison non-aero external components
A-30m	Align for aerocapture interface
A+20m	Jettison aeroshell
A+4h	Periapsis raise (circularization) burn
A+3y	End of mission

Once the Solar Electric Propulsion Module's (SEPM) job is done at around 2.5 AU, it is jettisoned to eliminate mass and solar array perturbations for later TCMs. The Orbiter uses a combination of Doppler ranging, ΔDOR, and optical navigation[4] to setup the AP entry trajectory delivery at entry minus 30 days.

Figure 2 illustrates the final aerocapture trajectory. The Orbiter spins up providing the AP with attitude stabilization, and then separates the AP. The Orbiter de-spins and performs a separation maneuver designed to put 3 hours of separation between the AP and Orbiter atmospheric entries. This allows the Orbiter to receive AP critical event data during AP entry, descent, and initial checkout. The Orbiter relays this data to Earth before it enters Titan's atmosphere. Approximately 1 hour prior to Orbiter atmospheric entry, the Orbiter will eject all non entry system components (truss, radiators, antennas, etc), and then orient for entry.

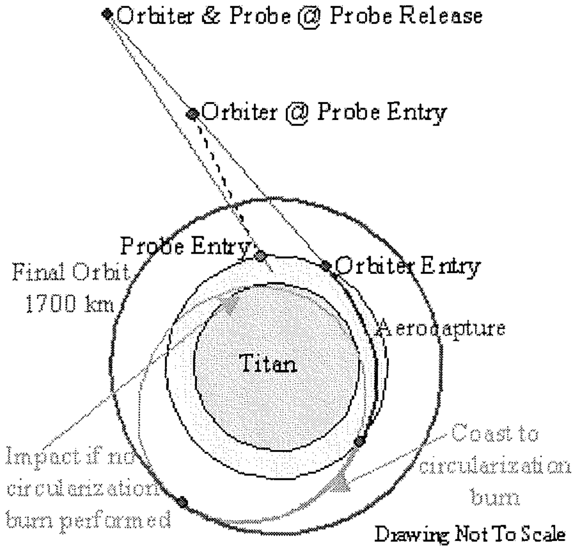

Figure 2. Aerocapture Trajectory

The primary heat pulse of aerocapture lasts less than 10 minutes, during which the Orbiter is actively controlling its bank angle with hydrazine thrusters. After atmospheric exit the aeroshell is jettisoned and the Orbiter prepares for the periapsis raise maneuver to insert the Orbiter into a 1700 km circular orbit.

4. MISSION SYSTEM DESCRIPTION

The Orbiter Flight System is the primary focus of this study and the Ground Data and Mission Operations Systems were not addressed. The SEPM is largely inherited from previous study and the AP is treated as a black box. The Launch and SEP configurations are shown in Figures 3 and 4, respectively. The launch system mass summary is shown in Table 2. The post SEP cruise configuration is shown in Figure 5.

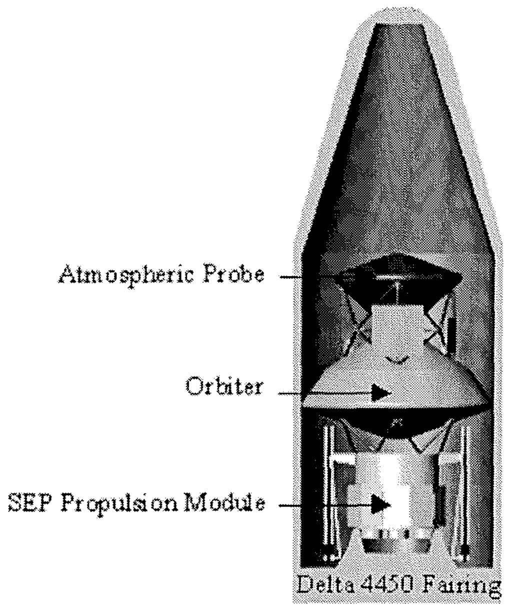

Figure 3. Launch Configuration

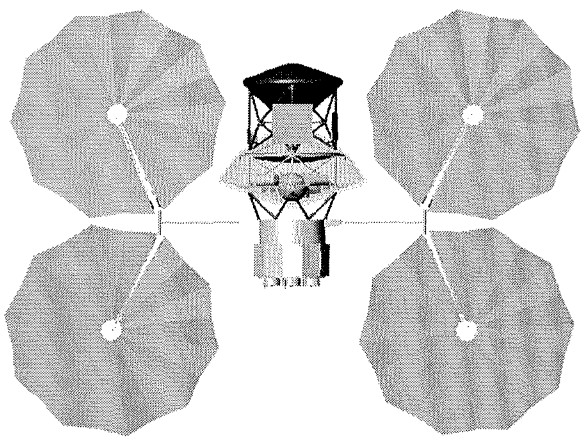

Figure 4. SEP Burn Configuration

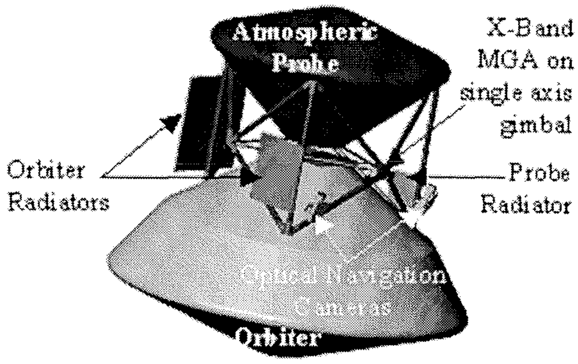

Figure 5. Post SEP Cruise Configuration

Table 2. Launch Mass Summary (kg)

Element	CBE	GC	GE	A
Atmospheric Probe	280.2	29.8%	363.8	400.0
Orbiter/AP Interface	47.5	30.0%	61.8	61.8
Orbiter Dry Mass	743.0	28.4%	954.0	1200.0
Orbiter Prop Mass	140.6	2.2%	143.7	
SEP/Orbiter Interface	47.3	30.0%	61.4	61.4
SEP Dry Mass	623.9	29.9%	810.4	1450.0
SEP Prop Mass	460.1	10.0%	506.1	
Launch/SEP Interface	60.0	30.0%	78.0	78.0
Dry Mass (DM) Totals	1801.9	29.3%	2329.4	2601.4
Prop Mass (PM) Totals	600.7	8.2%	649.8	649.8
Stack Total	2402.6	24.0%	2979.2	3251.2

Launch Vehicle Capability	3423	LVC
Launch Wet Mass Margin	29.8%	(LVC - CBE) / LVC
System Reserve	13.0%	(LVC - Growth) / LVC
Launch Dry Mass Margin	35.0%	

CBE = Current Best Estimate
GC = Growth Contingency = (GE - CBE) / CBE
GE = Growth Estimate
A = Allocation from system
Launch Dry Mass Margin = same as Launch Wet Margin with total propellant mass subtracted from all estimates.

4.1 Key Mission System Trades

Several trades associated with the overall Flight System are worth mentioning. These trades do not represent the a complete trade space for the Titan mission only those trades which drove the configuration of the flight system to allow convergence of a mission concept and determine aerocapture system feasibility.

4.1.1 Launch Stack Configuration

The orientation and placement of the AP and the Orbiter on top of the Propulsion Module (PM) drove the structural mass of the adapters as well as the primary structure mass for the PM and the orbiter. In general, 4 configurations were analyzed: the Orbiter and AP in nose up and nose down configurations with the Orbiter below and above the AP. The final configuration selected was Orbiter nose down (with respect to the launch vehicle) below the AP oriented nose up.

For all configurations of the Orbiter above the AP, the PM to Orbiter adapter became complex and massive. Additionally the large Orbiter mass suspended high on the launch stack resulted in much higher SEPM structure mass to accommodate the lateral launch loads and frequencies.

The Orbiter / AP orientation was selected as tail to tail for two reasons. First, there are potentially three separation planes between the Orbiter and the AP: Orbiter/AP, Orbiter/Truss, and AP/Truss. Each separation plane poses scarring risks to the TPS of the Orbiter and AP. Second, the structural interface of the truss with each vehicle is a risk to the TPS burn through (interface results in localized thermal anomalies). Routing the structural interface through the aft body lowers these risks.

The resulting stack configuration routes the primary PM to Orbiter adapter structure through the Orbiter fore body TPS. An engineering solution to the localized thermal anomalies at the interface with the TPS is considered solvable, but at the same time, it is considered highly desirable to find an alternate configuration which avoids perforation of all fore body TPS.

4.1.2 Cruise Propulsion System

A SEPM was selected over a chemical stage for the Earth to Saturn trajectory because of the SEP trajectory's superior overall performance in terms of delivered mass, flight time less than 6 years, and atmospheric entry velocity of around 6.5 km/sec. A detailed discussion of the chemical versus SEP trade is addressed by Noca, *et al.*[3]

4.1.3 AP / Orbiter Delivery

The delivery of the AP and the Orbiter to their respective entry trajectories could be performed by the Orbiter or by the SEPM. Since the aerocapture phase required the Orbiter to have all the subsystems required to perform AP and Orbiter delivery, the Orbiter was selected to perform these entry trajectory deliveries. This allowed deletion of the ACS, C&DH, and telecom subsystems from the SEPM and the separation of the SEPM soon after its burn out.

4.1.4 Probe Entry and Descent Data Relay

The AP critical event relay during entry and descent is a multi dimensional trade involving delivery errors (Orbiter and AP), telecom (AP and Earth), and Orbiter atmospheric entry risk (late separation of non entry system components). The selected strategy may not be the best solution, but is adequate to show feasibility for this study. The aspects of the Probe to Orbiter relay link are discussed in more detail in a later section.

Critical events relay using the SEPM on a flyby trajectory was ruled out because this would require the SEPM to be an independent spacecraft with unnecessary functional duplication with the Orbiter.

4.1.5 Titan Orbit Altitude

The initial desired science orbit altitude was specified at 1400 km. Orbit maintenance analysis performed by LaRC showed that for ballistic coefficients similar to the Orbiter design, as much as 100 m/s would be required for a three year mission – resulting in more propellant mass than the Orbiter could carry in our reference mission. The same LaRC analysis showed less than 2 m/s if the altitude was raised to 1700km. The only impact from a higher orbital altitude was to the science instruments. Since none of the specific instruments exist at this time, it was determined that the instrument impact was acceptable. Actual atmospheric density results from the Hyugens probe may provide an opportunity to lower this altitude if necessary.

5. ATMOSPHERIC PROBE DESIGN

As stated earlier, the AP design is considered to be a black box and out of the scope of this study. There are internal JPL studies performed by Team-X[12] indicating that 400kg is an adequate allocation for a Titan AP.

6. SEP MODULE DESIGN

A SEPM was selected over a chemical PM for the overall combination of shorter flight time, lower entry velocity, and lower PM mass; this trade is discussed in more detail by Noca[3]. An existing JPL SEPM design was modified for the Titan mission. The primary modifications were deleting the avionics in favor of using the Orbiter's avionics and increasing solar array structure and power capability. The SEPM structural mass was analyzed to assure proper launch load and frequency capability for the entire launch stack. The SEPM mass summary is shown in Table 3.

Table 3. SEP PM Mass Summary (kg)

Element	Flt Unit	CBE	GC	GE
SEP Wet Mass (kg)		1084.0	21%	1316.5
Xenon Propellant		460.10	10%	506.11
SEP Dry Mass	56	623.93	30%	810.40
ACS, C&DH, Telecom	3	5.85	30%	7.61
Power	7	148.31	30%	192.80
Structure	14	281.39	30%	365.81
Propulsion	20	142.28	30%	184.97
Thermal	12	46.10	28%	59.21

Most of the Attitude Control System (ACS), Command & Data Handling (C&DH), and Telecom functionality was moved to the Orbiter or to the Orbiter / Probe structural interface. This eliminates unnecessary component duplication through the entire system and allows the SEPM to be jettisoned after its job is complete. The majority of the Power system mass is the 25.6 m^2, 178 kg (growth), of solar arrays. The "Ftl Unit" column of Table 3 specifies the number of line items in the detailed mass list for the respective subsystem.

7. ORBITER DESIGN

The Orbiter design is shown in Figures 6, 7 and 8. Figure 6 shows the Orbiter in the Post AP release configuration. This configuration shows the critical components required by the Orbiter through post launch, SEP cruise, and AP entry and descent. These elements include Orbiter electronics and MMRTG radiators, X-Band MGA, AP UHF Relay antenna, and optical navigation cameras. Figure 7 shows the aerocapture configuration and Figure 8 specifies the primary Orbiter components.

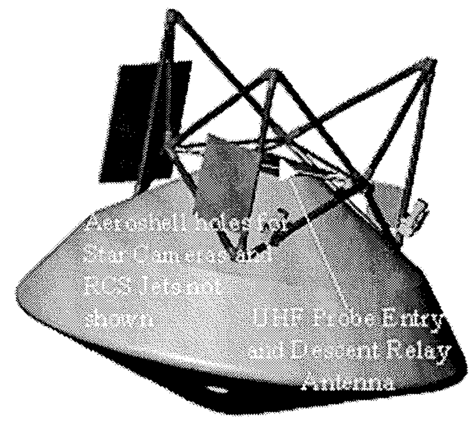

Figure 6. Post AP Release configuration

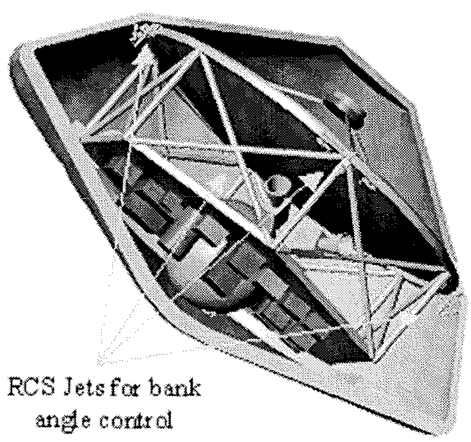

Figure 7. Aerocapture Configuration

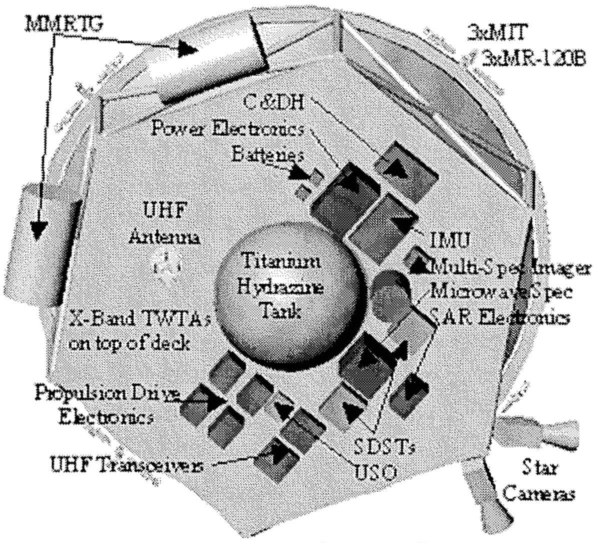

Figure 8. Titan Orbit Configuration

The estimated power required for the various mission phases is summarized in Table 4. Heater power in all phases is minimal because of an assumption that the MMRTG excess heat, ~3700W, can be distributed across the spacecraft well enough to not require the heater power typical for deep space missions. The modes listed in Table 5 are not all the modes identified in the study, just the ones that stress the system. The available power listed is the power output of two MMRTGs after 1.5% output degradation per year. It is assumed that once the telecom and instrument components have been turned on, that they are never turned completely off, but rather are placed in a low power standby mode when not in use. The 25% margin shown in the table is typically considered not viable for a pre-project, but specific opportunities to improve this are noted in the power subsystem section.

Table 4. Orbiter Average Power (W)

	Mission Phases				
	Cruise	Aero Capture	Lander Relay	Orbit Science	Earth Comm
Margin	38.1%	46.6%	32.4%	26.9%	25.0%
Available	226	226	222	214	214
Totals	*140.00*	*120.60*	*150.00*	*156.50*	*160.50*
Instrument	1.5	1.5	18.0	70.5	18.0
ACS	40.1	44.2	40.1	40.1	40.1
C&DS	14.9	14.9	14.9	14.9	14.9
Power	3	3	3	3	3
Propulsion	0	27	0	0	0
Telecom	76.5	30.0	66.0	20.0	76.5
Thermal	4.0	0.0	8.0	8.0	8.0

Table 5 presents the Orbiter mass summary with subtotals for Titan orbit, entry, and launch mass. All components are block redundant except for structure, propulsion, antennas, MMRTGs, thermal radiators, and science instruments. Generally, the Orbiter design was driven towards single fault tolerance without mission loss. Generally, a growth contingency (GC) of less than 30% in Table 5 indicates where components of high heritage are utilized in the system design. Instruments, structure, power, and thermal are the primary new development subsystems.

Table 5. Orbiter Mass List Summary (kg)

Orbiter Element	Flt Unit	CBE	GC	GE
Launch Wet Mass		**883.6**	**24%**	**1097.7**
Total Propellant		140.6	10%	143.7
Total Dry Mass	293	743.0	28%	954.0
Cruise Support Mass		65.5	9%	71.6
Propellant		41.4	0%	41.4
Dry Mass	49	24.1	25%	30.2
Structure & Misc	7	8.2	16%	9.5
Thermal	42	15.9	30%	20.7
Atmos Entry Wet Mass		818.1	25%	1026.1
Aerocapture System		416.7	24%	515.0
Propellant		88.9	0%	88.9
Bank Angle Control		12.6	0%	12.6
Circularization dV		76.3	0%	76.3
Dry Mass	8	327.8	30%	426.1
TPS	2	177.3	30%	230.5
Structure	6	150.5	30%	195.6
Titan Orbit Wet Mass		401.4	27%	511.1
Propellant		10.3	30%	13.4
Dry Mass	236	391.1	27%	497.7
Instruments	4	32.8	30%	42.6
ACS	15	20.2	10%	22.2
C&DH	16	15.3	26%	19.2
Power	5	80.1	30%	104.1
Telecom	13	39.1	24%	48.4
Structure	7	136.7	30%	177.7
Propulsion	73	39.5	21%	47.8
Thermal	103	27.4	30%	35.7

7.1Key Flight System Trades

7.1.1 Reaction Wheels vs. Thrusters

The approach navigation and the science teams would prefer reaction wheels for attitude control rather than RCS jets. Unfortunately, the 2 MMRTG design could not supply enough power to operate 3 reaction wheels and everything else needed for science data gathering. Minimum Impulse Thrusters (MIT), TRL 6 in 2004, were selected as a compromise providing the necessary stability for science pointing, but degraded performance for approach navigation (small forces integration). The navigation analysis performed by Haw[4] considers a spacecraft with reaction wheels; this inconsistency was not resolved before the end of the study.

7.1.2 Rigid vs. Deployable X-Band HGA

The selected 2.4m Fixed HGA selected provides a 2.3 Tbit data return capability to a 70m station assuming one 8 hour contact every day. This falls well short of the ~11 Tbits generated by the science instruments. A 6 meter deployable HGA was investigated, but it was not able to be incorporated into the design before the end of the study. Follow-on work for a Neptune aerocapture mission has since determine a deployable HGA is a feasible concept for the Titan mission timeframe. A 6 meter antenna would provide a 500 kbps return link capable of returning 15 Tbits and provide an opportunity to reduce the aeroshell diameter and change the backshell design to a single angle. Such an antenna would increase pointing knowledge and control requirements, but these requirements are to be within the capability of the MIT RCS based ACS system. The larger antenna would also affect the SAR instrument design because of the narrower beam width – higher resolution, but possible less than global coverage.

7.2 Subsystem Descriptions

Orbiter subsystems will be discussed in order of overall system impact. In general, subsystems discussed first drive the system design more than those discussed last.

7.2.1 Aerocapture System

The aerocapture system is defined as the TPS, the underlying aeroshell structure, the propellant required for attitude control during aerocapture, and the propellant required for the orbit circularization burn at the apoapsis of the aerocapture exit orbit.

The aerocapture system structure, TPS and their associated aero-thermal design basis are described in more detail by Justus, et al[5] (Titan atmosphere), Masciarelli, et al[6] (Guidance algorithms), Way, et al[7](Simulation), Takashima, et al[8] (Aerothermodynamics), Oleiniczak, et al[9] (Radiative heating), and Laub[10] (TPS).

The study team started with the largest possible aeroshell, 3.75m diameter, that would fit inside a 4m launch vehicle fairing in anticipation of needing a large diameter high gain antenna. As discussed earlier, changing to a deployable HGA would allow a smaller diameter aeroshell. The selection of the 70 degree cone angle is discussed by Masciarelli, et al[6].

7.2.2 Telecom

The Orbiter telecom system supports two primary links, X-Band to Earth and UHF to the AP. Table 6 summarizes the driving data return links. The X-Band System utilizes SDSTs and 50W TWTAs for communicating to Earth. The UHF telecom system is based on a next generation Electra Radio.

Table 6. Orbiter Telecom Links

X-Band

Mission Phase	Orbiter Antenna (dBi)	Ground Station	Dist (AU)	Data Rate (bps)	Xmit Pwr (W)
Launch	-6, Patch	34m BWG	0.5	10	50
Cruise	24.8, Printed Dipole	70m	11	500	50
Aero capture	None				
Orbit Science	44.3, Fixed Dish	70m	11	75000	50

UHF

Mission Phase	Orbiter Antenna (dBi)	Probe Antenna (dBi)	Dist (km)	Data Rate (bps)	Xmit Pwr (W)
Probe Entry / Descent	-3 @ 30°, 2x2 patch	-3 @ 60°, Omni	85000	carrier only	4
Science Relay	5, Helix	-3 @ 60°, Omni	2050	64000	4

7.2.3 Power

At 10 AU, solar power was out of the question. A Mutli-Mission Radioisotopic Thermal Generator (MMRTG) unit was selected for the Orbiter power source. This unit is currently in development and should reach TRL 6 by 2006. The expected performance of the MMRTG is approximately 6.3% efficiency for a 2000W thermal input.

The efficiency of the units is tied to, among other things, the temperature differential of the unit. The 6.3% efficiency is related to a finned exterior radiating to space. Cooling the exterior of the unit below what is expected from the finned radiator design will yield better power output. There is a potential with the Orbiter's passive loop heat pipes to cool the surface of the MMRTGs to improve the power efficiency. To raise the power margin listed in Table 4 from 25% to 30% requires a power conversion efficiency of only 6.7%.

The power system includes 2 MMRTGs, total power available of 252W BOL, 214W at end of mission. Secondary batteries are included to help during peak periods with a typical assortment of battery charge controllers, power switching, and power conversion electronics.

7.2.4 ACS

Because of the limited power, reaction wheels were discarded in favor of thrusters capable of 0.7 mN-s impulses. All other ACS components are fairly standard equipment including star trackers, IMUs, and propulsion driver electronics. The Orbiter does not possess sun sensors because there is no critical need to sun point during a spacecraft upset. The Orbiter possesses 2 star trackers, 2 optical navigation cameras, and 2 C&DH strings which should suffice to allow the spacecraft to determine its attitude and point the HGA at Earth instead of solar panels at the sun during an off-nominal event.

7.2.5 Propulsion

The propulsion system is a blow down hydrazine monopropellant system with two sets of thrusters. The first set of thrusters is comprised of 12 MIT thrusters, each with a 0.7 mN-s minimum impulse capability to be used for fine attitude control. The MITs are currently in a flight qualification process on track for TRL 8 before 2006. The second set is comprised of 12 MR-120B engines, each with a 133.5 N force capability. The MR-120Bs are used for attitude control during aerocapture and for Titan orbit maneuvering.

Six thrusters are put on a dedicated line with latch valve, for a total of 4 latch valves, to ensure single fault tolerance (in degraded performance mode) against loss of mission. The single tank is a 74cm diaphragm tank with a Titanium shell.

7.2.6 C&DH

The C&DH system is JPL X2000[13] based. The cards selected are currently planned for TRL-6 by 2006, but an MRO based C&DH system might provide a lower risk technology solution in a sufficiently low mass and power package.

7.2.7 Thermal

The mission design presents several challenges for the thermal design:

1. The MMRTGs together generate over 3700W of thermal heat.
2. The MMRTGs are enclosed in an aeroshell designed to keep heat from getting in.
3. The radiator system has to be designed to work before, during, and after aerocapture
4. Inside the aeroshell, the system will experience solar distance of 0.95 AU (0.7 for Venus Gravity Assist) to 10 AU.

Because Venus gravity assists were considered in the mission trade space[3], a 0.7 AU minimum solar distance was assumed for the thermal design efforts. A ~30 node lumped mass model of the spacecraft was constructed to compute temperature distributions during the key mission phases for various design options. Titanium/Water loop heat pipes running to hot radiators mounted on the Orbiter / Probe truss were chosen to solve the problem of getting the heat out of the aeroshell, and these were found to work even in the 0.7 AU hot case at Venus. Aluminum / Ammonia loop heat pipes were also added to transport Orbiter electronics heat out of the aeroshell. A second set of Titanium/Water LHP carry MMRTG heat directly to the hydrazine tank.

The computational model results confirmed that all of the key avionics and propulsion components were maintained within prescribed operating temperatures during both the cruise to Saturn and after orbit insertion when the aeroshell was jettisoned and the orbiter exposed to the cold space environment at Titan.

For the aerocapture phase, it was assumed that the radiators were separated from the aeroshell 40 minutes before aerocapture and that the aerocapture lasted 20 minutes, a total of 60 minutes without radiators. The heat from the MMRTGs and from the high speed entry is simply absorbed by the thermal mass of the vehicle during this time. In the thermal analysis, the entry heating was approximated by an instantaneous jump to 250°C in the bondline temperature between the TPS and structure, which is a conservative assumpion. The results demonstrated that all orbiter components were within their operational temperature ranges; although some with small margins.

7.2.8 Structure

The structure is discussed in more detail by Hrinda[11]. In general, the Orbiter primary structural design was driven by:

1. LV frequencies for Orbiter and Probe.
2. Combined geometry constraints of SEPM, Orbiter, and Probe in LV fairing.
3. LV loads for Orbiter and Probe.

8. NEW TECHNOLOGY DEVELOPMENT

Of all the technologies proposed that are currently less than TRL 6, only the TPS materials require additional funding to test the materials against the radiative heat loads expected at Titan[9]. The other technologies that are not currently at TRL 6: MMRTG, SEP Engine, and SEPM solar arrays, are all currently funded to reach TRL 6 in the 2006 time frame. If none of these three technologies actually reach TRL 6 by 2006, then the mission could still be performed with the currently lesser (mass) efficient technologies and a larger launch vehicle.

9. RECOMMENDED ADDITIONAL ANALYSIS

Many questions and trades consistent with continued Phase A/B efforts were identified by the study team. A summary of these issues is presented below along with a general classification of the issue as a lien, or opportunity, or either.

- **Launch Vehicle**: Verify 4m fairing not available for Delta 4450 (Opportunity).
- **Launch Configuration**: Eliminate structure through primary TPS (Lien).
- **SEP Propulsion Module**: 1) Incorporate latest Glenn Research SEP Engine capability (either). 2) Develop solar array deployment sequence concept and verify associated structures and mechanisms mass (Lien).
- **Atmospheric Probe**: 1) Verify 400kg is adequate (either). 2) Develop separation plane concept between AP and Orbiter which handles AP spin eject and thermal issues (AP MMRTG radiators) for 30 day coast to entry interface (Lien).
- **Navigation**: Verify use of MITs does not degrade navigation performance beyond mission requirements (Lien).
- **Science Instruments**: Develop conceptual designs for Multi-Spectral Imager and Microwave Spectrometer and verify TRL, mass, power, volume estimates (Lien).
- **Power**: 1) Develop detailed power modes and profiles (either). 2) Verify 2 MMRTGs are adequate for full mission (Lein). 3) Verify conversion efficiency of MMRTG based on thermal design (Opportunity). 3) Verify EMI/EMC compatibility for component configuration (either).
- **Thermal**: Verify MMRTG heat can be effectively routed to hydrazine system (manifolds, lines, thrusters) to eliminate need for heaters (Lein).
- **Telecom**: 1) Investigate trade between Ka-Band system or 6m deployable antenna for X-Band system (either). 2) Verify UHF line of sight for AP-Orbiter link during EDL and science relay are consistent with antennas and pointing concept (Lien). 3) Add LGA/MGA for Earth acquisition prior to high bandwidth links (Lein).
- **Aeroshell**: 1) Optimize packaging for smaller aeroshell (Opportunity). 2) Verify heating and TPS for new ballistic coefficient (either).
- **Cost**: Generate cost estimate for complete flight system (either).

10. CONCLUSIONS

The study demonstrates general technical feasibility for a Titan Explorer Orbiter flight system designed to use aerocapture as the Titan orbit insertion mechanism. Many liens exist against the conceptual design presented, but opportunities balancing the liens also exist. A change from the medium launch vehicle to a heavy lift launch vehicle would help retire many of the leins without invalidating the feasibility of the mission concept. Technology readiness for the flight system is good with all major components currently being funded to achieve TRL 6 by 2006 to support a possible launch date as early as 2010.

11. ACKNOWLEDGEMENTS

The spacecraft and mission design described herein were built upon a Titan aerocapture mission study performed by JPL's Team-X[12]. Although the configuration presented here is very different from the Team-X design, the Team-X design provided a valuable reference point from which system wide trades could be evaluated more easily.

Personnel from Langley Research Center, Johnson Space Center, Ames Research Center, Marshall Space Flight Center, and the Jet Propulsion Laboratory[3,4,5,6,7,8,9,10,11] were instrumental in determine system level requirements and subsystem capabilities for trade and mission performance analysis.

Discipline experts at the Jet Propulsion Laboratory including Dave Hansen (Telecom), Brian Okerlund (Computer Aided Design), Jonathan Lam (Structural Analysis), John Huang (Antennas), Ray Baker (Propulsion), Rolando Jordan (SAR Instrument), Nick Mardesich (Solar Arrays), Bill Nesmith (MMRTGs); Applied Sciences Laboratory including Chern-Jiin Lee (thermal); Swales Aerospace including Michael Nikitnin (Loop Heat Pipes); all provided valuable input into the subsystem conceptual designs represented in this paper.

12. BIBLIOGRAPHY

1. Chyba, C. et al., "Report of the Prebiotic Chemistry in the Solar System CSWG", NASA internal report,1999.
2. Tamppari, L. et al., "Cassini/Huygens Follow-On Mission Study Science Report", JPL internal report, 2001.
3. M. Noca, R.W. Bailey, C.J. Sauer, and R.E. Dyke, "Titan Explorer Mission Trades from the Perspective of Aerocapture", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper Number AIAA-2003-4801, July 22, 2003.
4. R.J. Haw, "Titan Approach Navigation for the Titan Aerocapture Orbiter", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper Number AIAA-2003-4802, July 22, 2003.
5. C. Justus, A. Duvall, D. Johnson, "Engineering Level Model Atmospheres for Titan and Neptune", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper Number AIAA-2003-4803, July 22, 2003.
6. J. Masciarelli, E. Queen, "Guidance Algorithms for Aerocapture at Titan", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper Number AIAA-2003-4804, July 22, 2003.
7. D. Way, R.W. Powell, J. Masciarelli, B. Starr, K.T. Edquist, "Aerocapture Simulation and Performance for the Titan Explorer Misson", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper Number AIAA-2003-4951, July 22, 2003.
8. N. Takashima, B. Hollis, K. Sutton, M. Wright, J. Oleiniczak, "Preliminary Aerothermodynamics of Titan Aerocapture Aeroshell", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper Number AIAA-2003-4952, July 22, 2003.
9. J. Oleiniczak, D. Prabhu, M. Wright, N. Takashima, B. Hollis, K. Sutton, "An Analysis of the Radiative Heating Environment for Aerocapture at Titan", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper Number AIAA-2003-4953, July 22, 2003.
10. Laub, B., "Thermal Protection Concepts and Issues for Aerocapture at Titan", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper Number AIAA-2003-4954, July 22, 2003.
11. G. Hrinda, "Structural Design of the Titan Aerocapture Mission", 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper Number AIAA-2003-4955, July 22, 2003. .
12. T. Sweetser, et al., "Titan Lander Conservative Science 01-06", Team-X Report, June 4,5,8,15, 2001.
13. "Europa Orbiter/X2000 Avionics Development Industry Briefing", NASA/JPL, Pasadena, Ca, June 6, 2001.