An Aerobot For Global *In Situ* Exploration of Titan

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Abstract

This paper describes the design and component testing of an aerobot that would be capable of global *in situ* exploration of Saturn's moon, Titan, over a 6 to 12 month mission lifetime. The proposed aerobot is a propeller-driven, buoyant vehicle that resembles terrestrial airships. However, the extremely cold Titan environment requires the use of cryogenic materials of construction and careful thermal design for protection of temperature-sensitive payload elements. Multiple candidate balloon materials have been identified based on extensive laboratory testing at 77 K. The most promising materials to date are laminates comprised of polyester fabrics and/or films with areal densities in the range of 40-100 g/m^2. The aerobot hull is a streamlined ellipsoid 14 meters in length with a maximum diameter of 3 meters. The enclosed volume of 60 m^3 is sufficient to float a mass of 234 kg at a maximum altitude of 8 km at Titan. Forward and aft ballonets are located inside the hull to enable the aerobot to descend to the surface while preserving a fully inflated streamlined shape. Altitude changes are effected primarily through thrust vectoring of the twin main propellers, with pressure modulated buoyancy change via the ballonets available as a slower backup option. A total of 100 W of electrical power is provided to the vehicle by a radioisotope power supply. Up to half of this power is available to the propulsion system to generate a top flight speed in the range of 1-2 m/s. This speed is expected to be greater than the near surface winds at Titan, enabling the aerobot to fly to and hover over targets of interest. A preliminary science payload has been devised for the aerobot to give it the capability for aerial imaging of the surface, atmospheric observations and sampling, and surface sample acquisition and analysis. Targeting, hovering, surface sample acquisition and vehicle health monitoring and automatic safing actions will all require significant on-board autonomy due to the over two hour round trip light time between Titan and Earth. An autonomy architecture and a core set of perception, reasoning and control technologies is under development using a free-flying airship testbed of approximately the same size as the proposed Titan aerobot. Data volume from the Titan science mission is expected to be on the order of 100-300 Mbit per day transmitted either direct to Earth through an 0.8 m high gain antenna or via an orbiter relay using an omni-directional antenna on the aerobot.

1. Introduction

Titan is a world that seems very well-suited to in situ exploration by buoyant, self-propelled robotic vehicles, also known as aerobots. This conclusion results from a combination of factors:

1. It has a dense atmosphere composed of high molecular weight gases. The nominal composition is 95% nitrogen, 2% argon and 3% methane for a mean molecular weight of 27.9. The atmospheric density (ρ) near the surface is 5.4 kg/m^3. This means that relatively large masses can be floated using modestly sized helium- or hydrogen-filled balloons.
2. The surface of Titan is thought to pose serious problems to surface mobility assets (rovers) because of the likely presence of liquid hydrocarbon lakes and oceans, plus possible "sticky" hydrocarbon sludges on the solid parts of the surface. Flying platforms are not impeded by these obstacles or the more conventional difficulties posed by hazardous terrain in the form of rocks or steep slopes.
3. Titan is completely cloud-covered and therefore surface imaging from orbital or fly-by spacecraft is limited to relatively low resolution radar and infrared maps. An aerial platform can provide high resolution aerial imaging over large surface

areas by flying below the clouds for long duration missions.

4. An aerobot can make in situ measurements of atmospheric properties over a range of altitudes.
5. The solar flux at Titan's surface is on the order of 1 W/m^2, a value much too small to enable solar-powered vehicles. Nuclear power provided by radioisotope decay is the only electric power source in the foreseeable future, with a likely output on the order of 100 W for a reasonably sized vehicle. This very limited available power strongly motivates the use of a buoyant vehicle so that no power has to be consumed providing lift as would be the case with an aircraft or helicopter.
6. Surface sampling from an aerial platform will require either a hovering capability or a low ground-relative speed. This is possible with an aerobot or helicopter, but not an aircraft.
7. Buoyant vehicles are inherently easier than aircraft or helicopters to safe in a fault scenario. An aerobot can remain aloft indefinitely with no power or control during recovery operations.
8. A long range aerobot does not require precision landing on Titan because it can fly to essentially any point of interest.
9. By flying at higher altitudes of about 8 km, the aerobot can take advantage of higher wind speeds (estimated to be 10-15 m/s) and circumnavigate Titan in less than a month.

Set against these advantages are two disadvantages: the larger aerobot size makes them more susceptible to wind-induced control problems during near-surface flight operations and it is a challenge to achieve sufficiently low buoyancy gas leakage rates needed for long mission lifetimes. However, these two problems are expected to be tractable leaving an aerobot as the preferred platform for future Titan exploration.

The scientific interest in Titan primarily stems from the presence of large amounts of organic compounds in its atmosphere and on its surface. To quote the National Academy of Sciences (NAS) Decadal Survey, "Titan provides a natural laboratory for the study of organic chemistry over temporal and spatial scales unattainable in terrestrial laboratories." (SSE Survey Committee, 2003) Titan's "pre-biotic" chemistry is thought to hold clues to the emergence of life on Earth and elsewhere and is therefore a top priority for future solar system exploration. The Decadal Survey articulated a few key elements that future Titan exploration should include (p. 132):

1. ". . . atmospheric mobility so that different levels, weather, and processes can be studied in detail with in situ experimentation. . . ."
2. ". . . high resolution remote observations of the surface from various altitudes. . . ."
3. ". . . descending to the surface multiple times during the mission to make close-range and possibly in situ measurements of surface composition and properties."

This paper will describe an aerobot that incorporates all of these elements along with a strawman instrument suite that can make the requisite scientific measurements. It builds on past studies that articulated early vehicle and mission concepts (Lorenz 2000, 2001; Jones, 2000; Hall et al, 2002). The proposed design described here should be viewed as a modified framework upon which to predict vehicle performance and explore engineering alternatives rather than an optimized final design. Our premise is that a Titan aerobot mission is a natural successor to Cassini-Huygens that will provide a substantial scientific return far beyond the alternatives of an orbiter, lander or surface rover.

2. Aerobot Requirements

Specification of aerobot requirements starts with an analysis of the Titan environment. Titan is the largest moon in the Saturnian system at 5150 km in diameter, which is approximately 50% larger than the Earth's moon and 5% larger than the planet Mercury. It is the only other world in the solar system besides Earth that features a dense, nitrogen rich atmosphere (95% N_2, 2% Ar, 3% CH_4). However, its great distance from the Sun (1.4 x 10^9 km) and total cloud cover result in a very cold surface of approximately 90 K. Figure 1 shows the predicted variation of atmospheric properties as a function of altitude using the "recommended" model described in Yelle et al (1997). Current models of aerosols and precipitates indicate, ". . . condensed hydrocarbons and nitriles at 50-80 km altitude and methane clouds at 10-35 km altitude."[6] Methane particle sizes are expected to be in the range of 0.1 to 50 microns with a nominal aerosol density of 1 g/cm^3. Methane ice is expected to exist at 14 km altitude near the equator and 19 km near the pole (Lorenz, 2002b).

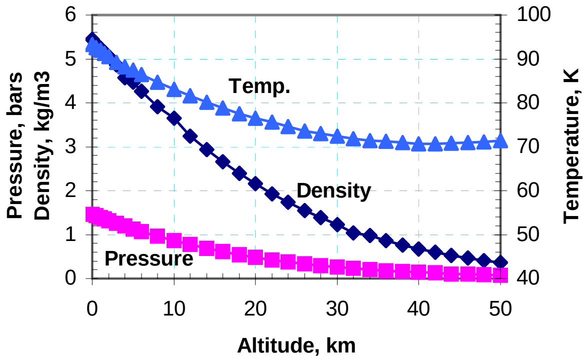

Figure 1: Properties of Titan's lower atmosphere (Yelle 1997)

The bulk density of Titan indicates a 50:50 mix of rock and ice. It is expected that most of the rock is located in the core leaving primarily ices and volatiles at the surface. Recent observations (Griffith et al, 2003) suggest that the surface includes both bare ice and organic material covered regions. The surface gravity is only 1/7 that of Earth at 1.35 m/s^2. Solar illumination on the surface is approximately 1 W/m^2. Ground-based radar measurements (Campbell, 2003) indicate the presence of smooth surface regions that could be interpreted as liquid hydrocarbon lakes or oceans. The actual topography is unknown, but estimates of maximum elevation are in the range of 2 km (Lorenz, 2002b) Near surface winds are expected to be < 1 m/s up to an altitude of a few hundred meters (the planetary boundary layer thickness). The vertical gradient is estimated to be in the range of 1 to 2 m/s per kilometer of altitude, so that at 10 km altitude the winds are predicted to be 10-20 m/s with a primarily zonal (eastward) wind direction.

The aerobot functional requirements result from a combination of these Titan environmental constraints with the science and mission objectives. They must necessarily be preliminary in nature given the uncertainties in knowledge about the Titan environment and the detailed science objectives that the next mission will emphasize. Table 1 summarizes the requirements adopted by the authors for a mission to Titan launching in the 2010 – 2015 time frame that would be capable of addressing the science goals articulated in the NAS Decadal Survey. The functional requirements are a mixture of thermo-mechanical features and artificial intelligence to enable highly autonomous operations. The need for autonomous operation is motivated by the greater than two hour time delay between the transmission of a command signal from the Earth and receipt from the aerobot indicating that the command had been executed. Such large latencies make teleoperated control impractical for near-surface flight operations like obstacle avoidance and sample collection. The autonomous operation functions in Table 1 presume a long duration mission that performs multiple surface sample acquisitions; however, far less autonomy is required for less ambitious missions that do not include near surface flight and surface sample acquisition.

The 200 kg floated minimum mass requirement resulted from an iterative design process that factored in the expected masses of all the aerobot components plus approximately 30% for a mass contingency. This mass includes a >30 kg allocation for science instruments and sample collection hardware. A detailed breakdown of this mass in the final design is presented in the next section as Table 3. The 14 km altitude listed as the desired goal is intended to avoid the possibility of methane icing on the aerobot; however, we were willing to accept as low as 8 km maximum altitude to ease the overall design problem while preserving the ability to achieve the primary science goals on the surface and in the deep atmosphere. Similarly, the 6 month mission lifetime was a compromise between the difficulty of ensuring a sufficiently low buoyancy gas leak rate versus the desire to collect as much data as possible from widely scattered points on the surface. The use of a nuclear power supply will certainly allow for much longer missions if the vehicle is sufficiently robust and avoids damage during initial operations.

Although most of the details of a Titan aerobot design are independent of the overall mission architecture, the following aspects have been assumed for this design effort:

1. A 6 year trip time from Earth to Titan using solar electric propulsion (e.g., Lockwood, 2003).
2. Direct entry into the Titan atmosphere upon approach with the aerobot delivered inside of a protective aeroshell. Huygens-like heritage is assumed for the aeroshell and parachute systems.
3. Existence of a Titan spacecraft aerocaptured into orbit within hours of the deployment of the aerobot (e.g., Lockwood, 2003). Since the aerobot is planned to use direct to Earth

Table 1: Summary of Baseline Titan Aerobot Requirements

Functional Ability	Figure of Merit-1	Figure of Merit-2	Present State-of-the-Art	Minimum Requirement	Desired Goal	Comments
Fly in a cryogenic environment	Lowest operating temperature	Balloon material areal density	-20 C, 300? g/m^2	90 K, 200 g/m^2	90 K, 150 g/m^2	Driven by balloon material temperature compatibility
Carry useful payload mass	Non-balloon mass carried	Hull volume	N/A for cryogenic environment	200 kg, 60 m^3 hull volume	400 kg, 140 m^3 hull volume	Larger sizes will enable a more comprehensive set of science instruments
Perform aerial deployment and inflation (D&I)	Mass of D&I system	Time to inflate airship hull	N/A for cryogenic environment	120 kg, 20 min inflation	80 kg, 10 min inflation	Need to avoid ground contact for all mission phases
Fly for long durations	Flight lifetime	Distance flown	N/A for cryogenic environment	6 months, 15000 km	12 months, 30000 km	Limiting factors are buoyancy gas loss and mechanism wear-out
Change Altitude	Altitude range	Rate of change	N/A for cryogenic environment	0 - 8 km, 0.3 m/s	0 - 14 km, 1.0 m/s	Achieved through thrust vectoring and buoyancy control
High efficiency electrical propulsion	Cryogenic electric motor efficiency	Propeller efficiency	motor 60%, propeller 90%	motor 70%, propeller 90%	motor 90%, propeller 90%	Very limited electrical power but nuclear energy is infinite; must operate for up to 1 year
Autonomous vehicle diagnosis, HDA and safing	Detection probability of high-impact events	Maximum time of safe operation	40%, 1 hr	80%, 4500 hrs	99%, 9000 hrs	Round-trip light-time limits utility of ground intervention
Onboard mission planning and monitoring	Number of activities in plan	No-contact time period	100 activities, 1 hr	1000 activities, 200 hrs	2000 activities, 400 hrs	Assumes nominal time without Earth contact of 8 days (1/2 Titan orbit)
Autonomous "go to" and station-keeping flight capability	position knowledge	relative control capability	N/A	position +/- 1 km, control +/- 100 m	position +/- 0.5 km, control +/- 20 m	Titan is both GPS-denied and mostly stellar reference-denied due to clouds
Sensor-based science target acquisition and tracking	Tracking persistency	Visual servoing accuracy	10% target size/distance, 5% accuracy	5% target size/distance, 2% accuracy	1% target size/distance, 1% accuracy	Dependent on surface texture, atmospheric transparency and illumination conditions
Autonomous surface sample acquisition	target size	type of material	N/A	100 m targets, loose or liquid material	20 m targets, loose, liquid or solid material	Samples must be acquired without landing the aerobot

telecommunications via a high gain steerable antenna, this orbiter is only expected to play a backup role as a telecom relay. However, it will also have significant value as a navigation source and as a generator of orbital science data.

4. Delivery of the aerobot into the high northern latitudes (> 60 N) to take advantage of the summer solstice season on Titan circa 2017. Summer solstice means that the north polar region is continuously illuminated by the sun and is in continuous view of the Earth. This timing can serve as an important risk mitigation step by allowing the early aerobot flight operations to be conducted in daylight and in continuous telecom with Earth.

3. Design Description

Our team utilized a design and development approach based on an extrapolation of Earth airship and robotic technologies to the Titan aerobot problem. Three factors combine to make this a useful approach:

1. Titan and Earth both have dense nitrogen-rich atmospheres that will yield comparable flight aerodynamic parameters such as Reynold's number and pressure coefficient.

2. Earth airships have over a century of accumulated design and development experience that has yielded highly optimized designs.
3. Flight testing of a Titan aerobot must be done on Earth and this testing will be facilitated by the use of Earth derivative designs.

As a result, our proposed configuration bears a lot of similarity to conventional Earth airship designs. Figure 2 is a schematic diagram of our vehicle with various key metrics noted. The streamlined ellipsoidal shape provides a very low drag coefficient in the range of 0.02 to 0.03 based on the Earth airship experience across a wide Reynold's number range of 10^6 to 10^8 (Curtiss et al, 1975). Following standard airship usage, we define the drag coefficient, C_D, and Reynold's number, Re, as:

$$C_D = \frac{Drag}{\frac{1}{2}\rho u^2 V^{2/3}} \quad (1)$$

$$R_e = \frac{\rho u L}{\mu} \quad (2)$$

where ρ is the density, u is the velocity, V is the hull volume, L is the hull length (nose to tail) and μ is the viscosity. Substituting values for near surface Titan flight at a velocity of 2 m/s we find that the drag equals 4 N and the Reynold's number is 2.2 x 10^7. This low value for drag is for the bare hull only, with the gondola and tail assembly expected to approximately double this value. But even a drag force of 8 N corresponds to a power input of only 16 W at 2 m/s (power equals drag times velocity) which should be supportable with a 100 W power supply given reasonable powerplant and propeller efficiencies.

The Titan aerobot employs a traditional twin engine configuration with a 1 m diameter propeller mounted on either side of the payload compartment. These propellers are 1-axis vectorable from vertically up to vertically down to assist with altitude changes and to improve maneuverability and station-keeping functionality during near surface flight. Density changes across the 0-8 km altitude range are accommodated with 20 m^3 of internal ballonets (33% of the total volume) equally divided fore and aft. These ballonets are filled with redundant blowers located inside the payload compartment and connected with 10 cm diameter flexible pipes along the bottom of the hull. A nominal superpressure of 200 Pa will be sufficient to keep the envelope fully inflated, although the current design can tolerate over 2000 Pa with a safety factor of 4 under conservative operating assumptions.

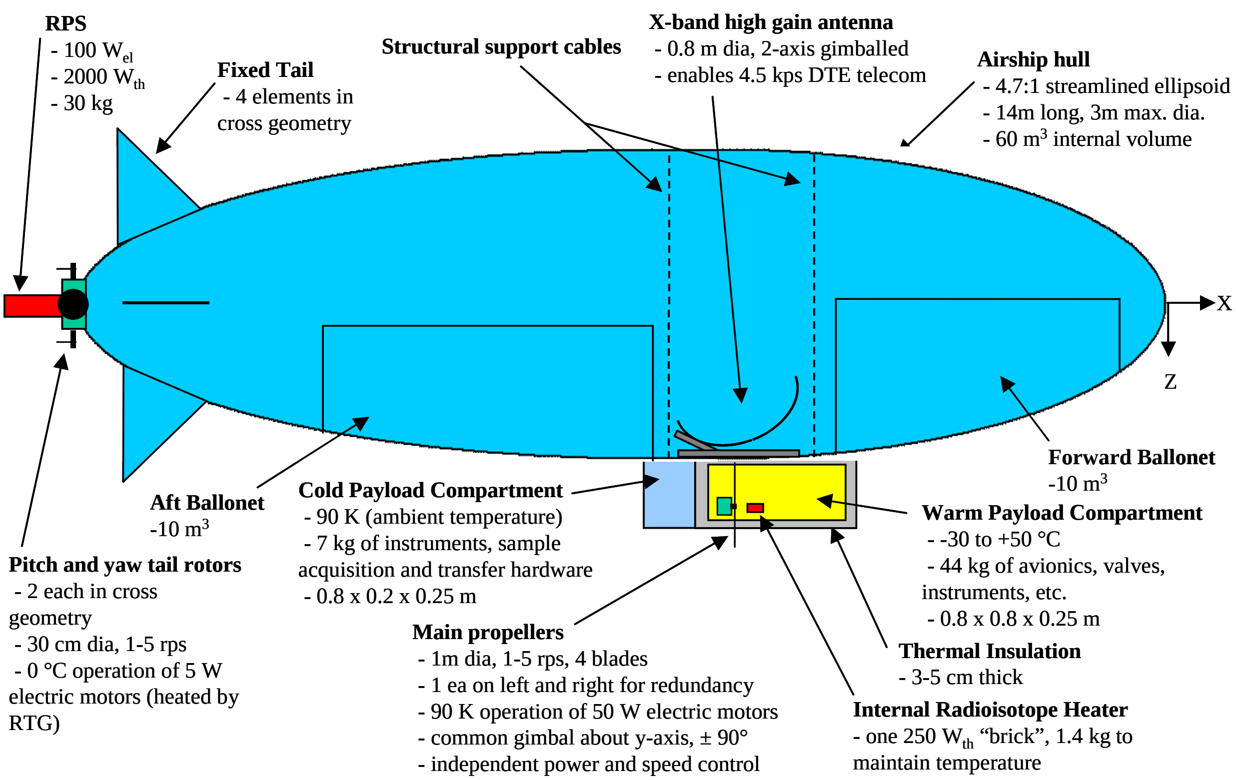

Fig. 2: Schematic Diagram of Titan Aerobot.

The tail design is a combination of conventional and novel elements. The near surface flight speed of 0-2 m/s on Titan results in a very low dynamic pressure (0 to 10.8 Pa) that limits the utility of traditional rudders and elevators to effect attitude control. Therefore, our design employs a four propeller arrangement (two vertical, two horizontal) to provide transverse tail thrust for pitch and yaw control. These four propellers provide for a very high degree of maneuverability even at zero relative wind speed. The design is also doubly redundant since the propellers can be operated in reverse to provide for bi-directional thrust in the event of a motor failure. Conventional, but unmovable, fins are also provided to assist with directional stability at higher flight speeds. The other unusual aspect of the tail design is that our main power source is located there. This is a multi-mission radioisotope power source (RPS) that produces 100 W of electric power from a total heat generation of 2000 W. The tail location ensures that only a small amount of the waste heat will transfer to the buoyancy gas in the hull, thereby avoiding the flight control complications of variable buoyancy due to variable flow conditions (cooling conditions) around the vehicle. Also, the exposed tail location provides adequate free convection cooling of the RPS under worst case conditions of the aerobot unpropelled and drifting with the winds, which allows us to avoid use of active thermal control devices like heat pipes or forced convection blowers.

The payload compartment is divided into cold and warm sections. The warm section houses most of the avionics and science instruments at an Earth-like temperature range of –30 to +50 °C. A single 250 W thermal RPS "brick" is placed in the warm chamber to augment electrical power dissipation and keep this compartment much warmer than the Titan environment. Thermal insulation is provided by 3 cm thick panels of aerogel on all sides of the compartment. The basic structure is aluminum honeycomb with internal mounting plates for the individual components. Windows are provided for the onboard cameras to image the Titan surface. The main telecom antenna is located on top of the compartment and inside the hull. This 0.8 m diameter X-band high gain antenna is two-axis gimballed to enable continuous pointing to within 0.6º of the Earth during normal aerobot flight operations. Preliminary link budgets indicate that a data rate of up to 4500 bits per second can be achieved with 15 W of radiated power to a 70 m antenna of the Deep Space Network. This translates into a daily data volume of 130 Mbits given an 8 hour transmission period. Experimental efforts to verify adequate tracking performance of a steerable antenna from a floating platform will be described in the next section. Behind the warm compartment is a smaller section that is not heated. This cold compartment houses the sample acquisition hardware that brings material into the aerobot. The specific design of this hardware remains an open issue at the time of this writing, so for current purposes we have simply made a mass, volume and power allocation for this equipment so that the design of the rest of the vehicle can go forward.

The Titan aerobot will be aerially deployed upon arrival at the 8 km altitude level. Aerial deployment is preferred to surface deployment because it avoids all of the potential problems of a rough or liquid surface that could damage the aerobot and/or interfere with the deployment and inflation process. Figure 3 shows a storyboard of the aerial deployment and inflation sequence. A mortar deployed drogue parachute deploys first and is used to pull off the aft cover of the aeroshell. The aft cover separation triggers a cascade of deployments as the subsequent elements of the flight train are pulled out of the aeroshell one after the other: main parachute, payload compartment and airship hull. The shock forces associated with this deployment sequence are mitigated by the use of energy-absorbing ripstitch in series with the connecting tethers. Note that these shock forces do not go through the relatively more fragile balloon material of the hull with this vertical configuration. There will be shear forces at the payload compartment – hull interface, but these are smaller and easily designed for. After this initial deployment, the flow of hydrogen buoyancy gas is started via pyrotechnically activated valves. The fill duration is nominally 10 minutes for the 16.8 kg mass of gas, during which the vehicle will descend at approximately 5 m/s from 8 to 5 kilometers of altitude. After inflation, the parachute and the aeroshell are sequentially detached and the aerobot rotates into its normal horizontal flight orientation. The aerobot should be close to neutrally buoyant at this point and will maintain altitude and drift with

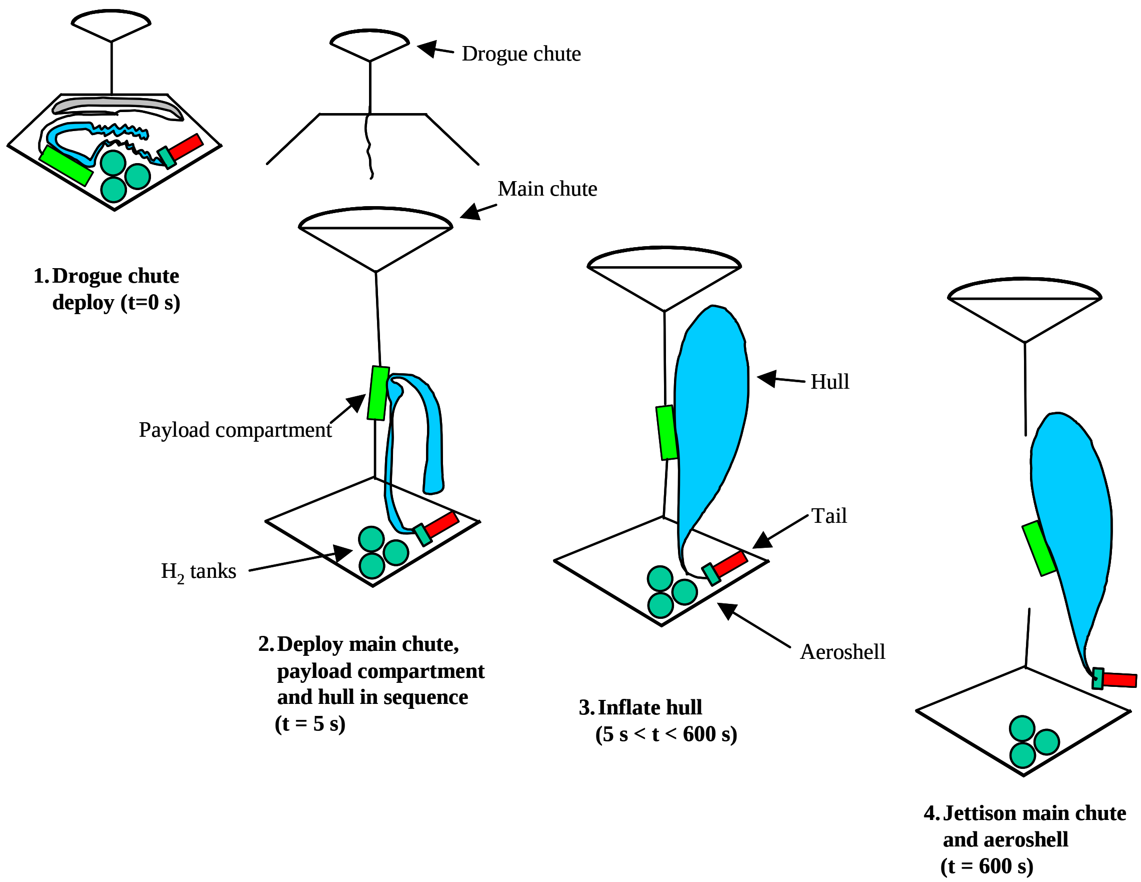

Figure 3: Aerial Deployment and Inflation Sequence

the wind while the ballonets are filled with atmospheric gas to fully inflate the hull to its nominal superpressure value of 200 Pa. At this point the aerobot will be ready for powered flight operations.

Global navigation and position localization will require a fusion of multiple data sources. Both the Sun and the Deep Space Network (DSN) transmitters can serve as a directional radio frequency source while in view. An orbital spacecraft at Titan can also serve as a known radio location if the mission uses a combined orbiter plus aerobot approach. Both the Sun and Saturn can serve as infrared sources that can be detected below the clouds by the aerobot. There is also a possibility of using other external sources like stars, quasars and the other Saturnian satellites, but detailed analyses have yet to be done to assess their feasibility. These external measurements will be augmented by in situ altimetric, inertial and imaging data on board the aerobot. However, the overall sensor fusion of external and internal data types has not been modeled at the time of this writing and therefore quantitative estimates for position determination performance are not available.

An overall mass summary is presented in Table 2 and a more detailed Master Equipment List (MEL) is presented as Table 3. The current best estimate (CBE) of the floating vehicle mass is 156.8 kg excluding hydrogen buoyancy gas. However, the hull volume has been sized such that a much larger total of 234 kg of gross buoyancy is produced. This allows for the usual 30% mass contingency (47.1 kg) on the vehicle mass with an additional 11.4 kg (7% of the CBE) for ballast to yield an aerobot with a +2 kg net buoyancy. In essence the combination of contingency and ballast provide a 37% mass margin on the CBE. In addition to this aerobot vehicle mass there is substantial non-floating mass required for the aeroshell (including parachutes and mechanisms) needed to protect the vehicle during atmospheric entry from space and for the aerobot deployment and inflation system. Simple scaling relations are used for estimating the mass of these two subsystems in lieu of a detailed design which does not yet exist. Specifically, the deployment and inflation system mass, which is primarily high pressure hydrogen tanks, is set to six times the hydrogen gas mass, and the aeroshell mass is set to 30% of the total entry mass. The total entry mass of ~600 kg is larger than the Huygens probe (350 kg) but is comparable to the Mars Pathfinder vehicle (585 kg) and modestly smaller than the Mars Exploration Rovers (827 kg).

Table 2: Overall Mass Summary

Mass Summary	Mass (kg)
Floating vehicle without gas	156.8
30% Contingency on floating mass	47.1
Hydrogen gas	16.7
Ballast to achieve 2 kg net buoyancy	11.4
Floating mass sub-total	**232.0**
Buoyancy provided by H2 gas	234.0
Net Free Lift	2.0
Deployment and inflation system	100.2
Aeroshell	181.0
30 % Contingency on non-floating mass	84.4
Non-Floating mass sub-total	**365.6**
Total Entry Mass	**597.6**

There is a rich instrument suite on the aerobot as listed in Table 3. This collection of instruments is not meant to be definitive, but simply serves as a point design capable of meeting most of the Titan in situ science objectives with a reasonable 20+ kg mass allocation. Note that the 15 kg mass listed for the sample acquisition and transfer subsystem is an allocation because no detailed design for it currently exists. The remaining masses in Table 3 are a mixture of high quality estimates derived from existing designs or hardware (ACS, C&DH, Power, Telecom, Hull, Ballonet) and allocations for less mature subsystems (Propulsion, Structure, Ballonet fill system). The current 43% mass margin serves as a powerful risk mitigation element against the likelihood that mass values will grow as the aerobot component and subsystem designs get done and the remaining technical issues become resolved. Further details on the hull material, steerable antenna and cryogenic motor components will be presented in the next section.

The peak power consumption of the aerobot is intentionally designed to be far in excess of the 100 W output of the RPS. In particular, we want to be able to divert close to all 100 W of power into the propulsion system to provide maximum maneuverability during hazard avoidance situations. Similarly, we want to be able to utilize most of this power for telecommunications during those times when the aerobot has temporarily finished data collection and does not need propulsion. In effect, the power to all subsystems will be heavily duty-cycled in a manner regulated by the onboard computer as part of its autonomous functioning protocols.

This Titan aerobot design contains several features that enhance its operational robustness for a 6-12 month mission. The most important features are:

1. Dual main motors and propellers. Given that power is a cubic function of flight speed, this enables the aerobot to fly with a failed engine at approximately 80% of the top flight speed (speed ~ power$^{(1/3)}$ ~ 0.5$^{(1/3)}$ = 0.79).
2. Dual attitude control motors and propellers for each of the yaw and pitch axes. As long as the motors are reversible, this provides attitude control in the event of a motor failure on each axis.
3. Dual blowers and quad redundant valves on the ballonet fill system. This enables filling and exhaust of both the forward and the aft ballonet in the event of both a blower and a valve failure.
4. 2 kg of net buoyancy are provided so that the aerobot will ascend to its maximum altitude of 8 km in the event of a total loss of power or propulsion. This is far above any surface topography and is therefore the safest place to be at Titan while troubleshooting activities are underway. Even if propulsion capability is not regained, the aerobot can continue to make science observations from this altitude.
5. An 0.5 kg (3%) hydrogen gas reservoir is carried in the payload compartment to be makeup gas in the event of hydrogen leakage out of the hull.
6. Use of an omni-directional X-band antenna to back up the primary X-band steerable antenna. The omni antenna can transmit ~1 bps of data and receive ~100 bps of command information from the Deep Space Network.
7. The radioisotope power source does not require active thermal control given its exposed tail location, therefore overheating is not a concern under any flight conditions.
8. Autonomous vehicle health monitoring, failure detection and recovery through a combined on-board software and sensor system.

Table 3: Master Equipment List

	Sub-system Mass (kg)	Com-ponent Mass (kg)		Sub-system Mass (kg)	Com-ponent Mass (kg)
Instruments	**21.5**		**Telecom System**	**15.3**	
Subsurface Radar		3.0	SDST transponder		2.9
Meteorology (P, T, precipitation)		1.4	SSPA		2.6
Atmospheric Acoustic Monitor		0.1	Gimbal		4.0
Cameras		2.3	High-gain X-band antenna		1.4
Magnetometer		0.4	UHF low-gain antenna		0.5
Laser/RF/Sonic Altimeter		0.8	UHF Transciever		3.0
Lightning/EM Radiation Detector		0.2	Diplexer		0.4
IR (RF) Atmospheric Radiometer		1.0	Cables		0.5
Net Flux Radiometer		0.2	**Propulsion System**	**8.0**	
Imaging Radar		3.0	Twin main propellers		1.5
GCMS		6.0	Twin main motors & linkages		2.5
Chemical Analysis		0.5	Quad tail assembly		2.0
Imaging Microscope		0.4	Cabling		2.0
IR/fluorescence spectrometer		2.2	**Payload compartment structure**	**15.0**	
Attitude Control System	**1.3**		**Payload compartment thermal**	**10.3**	
IMU (LN-200)		0.7	Aerogel insulation		8.3
3D Anemometer (airspeed)		0.3	RPS 250 W thermal "brick"		1.5
Sky IR camera/sun sensor		0.3	Fasteners		0.5
Command and Data Handling	**3.2**		**Sample acquisition & transfer**	**15.0**	
Flight computer		1.2	**Hull and ballonet system**	**24.0**	
Mass memory		1.0	Hull		13.4
Housing		1.0	Tail fins (4)		1.0
Power System	**43.3**		Ballonet membranes		3.0
Radioactive power source		38.0	Ballonet blowers (2)		0.6
Rechargeable batteries		2.3	Ballonet Valves (8)		2.0
Power distribution & control		3.0	H2 makeup gas system		4.0

Vehicle health monitoring, failure detection and recovery is just one aspect of the overall vehicle design for highly autonomous operations. Figure 4 shows a functional block diagram of the autonomy architecture that includes the elements needed to fly and collect surface samples at Titan with minimal intervention from controllers on Earth. This approach integrates accurate and robust vehicle and flight trajectory control, perception-based state estimation, hazard detection and avoidance, vehicle health monitoring and reflexive safing actions, vision-based localization and mapping, and long-range mission planning and monitoring. This overall functionality is required for near-surface flight operations involving close inspection of surface features or collection of surface material. Autonomous "go-to" flight capability is needed to reach specific targets of interest whether they be rocks, hydrocarbon lakes or geothermal hot springs. Go-to and stationkeeping operations are enabled by image-based vehicle motion and position estimation using a multi-sensor state estimation approach. A Kalman filter is used to fuse inertial navigation measurements (rotational velocities and linear accelerations) from the inertial measurement unit (IMU) with surface relative motion estimates derived from image-based motion estimation. In addition to an IMU and cameras, other key sensors include atmospheric temperature, pressure and wind speed (environment knowledge), altimeter (altitude) and onboard temperature, pressure and electrical power (health monitoring).

An aerobot is characterized by having different flight modes (take-off/landing, station-keeping/ hovering, ascent/descent, high-speed cruise, low-speed flight) that require alternative actuator control strategies and flight control algorithms. Important flight control challenges include non-minimum phase behavior and oscillatory modes at low speeds, time-varying behavior due to altitude variations, and variable efficiency of the actuators depending on aerobot speed. Our design employs mode-specific low-level controllers that use dynamic models of the airship and its environment. Since the aerobot will face constantly changing environmental conditions, adaptation is important in these control systems. Overall flight control and switching between flight modes is done using a hybrid supervisory control system based on a Petri net model.

Further details on the development status of the Titan aerobot autonomy system can be found in the next section and in Elfes et al (2003).

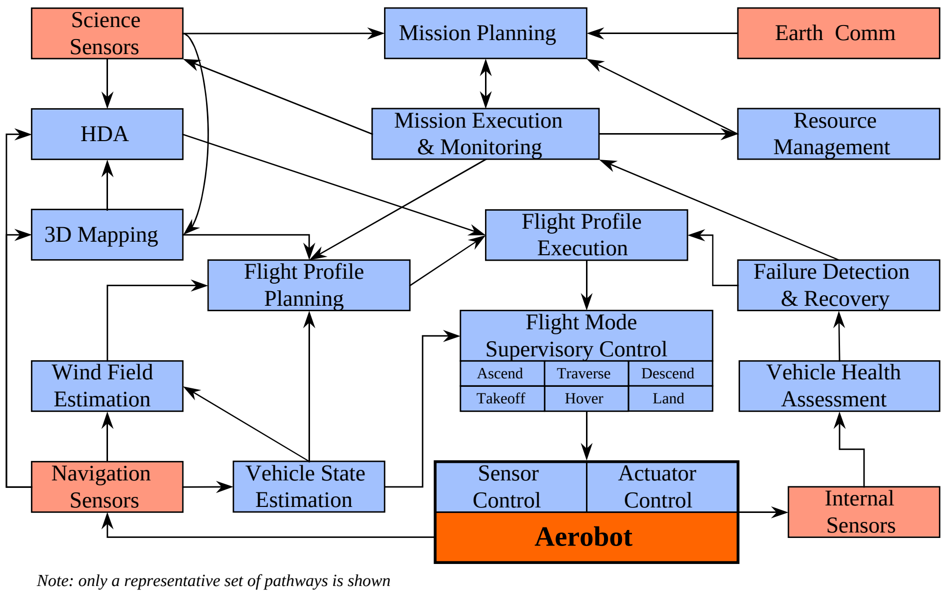

Fig. 4: Autonomy architecture

4. Experimental Results

The Titan aerobot design described in the previous section has been developed in conjunction with experimental activities in selected subsystems. The results from three key activities will be described in this section:

1. Cryogenic balloon material development.
2. Steerable antenna experiment.
3. Aerobot flight testbed for autonomy development.

The 80-90 K temperatures expected on Titan are far colder than anything an Earth balloon or airship has to tolerate. Therefore, a new cryogenic balloon material is needed that can meet the Titan aerobot requirements listed in Table 1. The approach we took was to experimentally investigate existing films, fabrics and coatings in various combinations rather than to try and invent new base materials. Even with immediate discounting of materials that are well known to be unsuitable for cryogenic operation, the parameter space for this approach is extremely large. Therefore, we focused our initial efforts on polyester, polyimide and fluoropolymer based materials produced as thin films, thin film laminates, coated fabrics or fabric plus film laminates. A total of 53 different samples were fabricated, with the most of the critical lamination and coating steps produced by our industrial subcontractors. An initial screening test was done on each sample at JPL using a Gelbo Flex Tester that repeatedly subjected the material sample to combined axial and torsional folding (Fig. 5). The material was immersed in liquid nitrogen and was tested for gas leakage every 100 or 200 cycles to quantify at what point the material became compromised. For these tests, the sample length was 20 cm, the axial compression per stroke was 5 cm, the torsional twist was 45º, and the frequency was 0.5 Hz. The results showed a wide range of performance with some materials unable to tolerate 200 cycles and others able to tolerate 4000 cycles. Generally speaking, polyester and polyester composite films tolerated 1000 to 4000 cycles, polyimide film tolerated only 200 cycles and the polyester fabric plus polyester film composites spanned a range of 200 to 1400 cycles. The actual Titan aerobot is expected to see material folding of some severity perhaps only in its initial packed condition and subsequent deployment upon arrival.

During normal flight the aerobot hull will be fully inflated and will not normally see any folding at all. It is not possible to translate the Gelbo flex test results into an unambiguous threshold for Titan aerobot suitability; therefore, we opted to pick the best film and the two best film plus fabric laminates for further development. Table 4 summarizes the key properties of these three materials, all of which survived in excess of 1000 Gelbo test cycles. Note that the 2000 Pa superpressure required of the Titan aerobot corresponds to approximately a 3000 N/m pull strength requirement before the safety factor is added. Therefore, the two fabric laminate materials provide an ample margin of safety compared to this value while the film-only material is marginal. However, it may be possible to increase the thickness of the film-only material to provide increased strength without compromising its flexibility. The mass estimate presented in Table 3 above is based on the 94 g/m^2 value of the moderate-weight laminate with 15% added for seams.

Figure 5: Gelbo flex testing machine with sample mounted

The second stage of material development consisted of fabricating adhesive seams on these three materials using different tapes and adhesives. Many samples of both butt and overlap seams were constructed by our industrial subcontractor GSSL. These samples were tested in the JPL Gelbo flex test machine at 77 K to ensure comparable cycles to failure compared to the parent material. This work is in progress at the time of this writing, but we can report that at least one adhesive plus seam geometry combination worked for each of the three materials.

Table 4: Properties of top 3 cryogenic balloon materials from flex test

Material	Areal Density (g/m2)	298 K Pull Strength (N/m)	77 K Pull strength (N/m)
Polyester film	41	3800	9100
Lightweight laminate (film + fabric)	75	8200	12800
Moderate weight laminate (film + fabric)	94	9100	16400

This success paves the way for full aerobot hull prototype construction based on relatively simple and inexpensive adhesive seams.

The second experimental area concerns the high gain steerable antenna located on top of the payload compartment inside the hull. We have completed some preliminary proof-of-concept ground tests of this concept using a commercial, off-the-shelf antenna designed for satellite television reception on marine vessels. The satellite tracking problem from a ship is similar to that faced by a Titan aerobot in that it requires on the order of 1º pointing accuracy to a fixed target with two-axis angular disturbances on the order of a few seconds time scale. We procured a KVH TracVision 4 antenna (Fig. 6) for our tests that has the following properties: 0.46 m diameter dish, 13.6 kg mass, Ku band (12.2 GHz), 3.7º beamwidth and a nominal tracking rate of 30 º/s. This antenna was suspended from a small crane and moved through a variety of simple pendulum motions while tracking the satellite. We confirmed the ability to track at angular rates of up to 30 º/s for angular displacements of up to 20º in any plane.

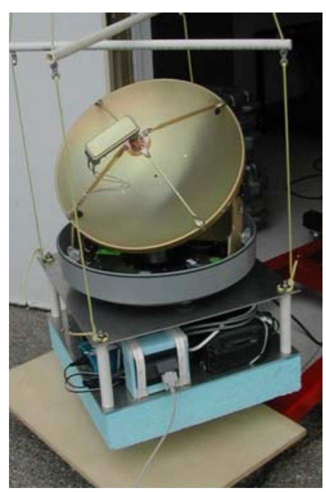

Fig. 6: KVH TracVision 4 antenna prior to ground test

This magnitude of disturbance is expected to be a representative upper limit of actual turbulence-induced motion during flight, an hypothesis will be evaluated in future flight tests from tethered and untethered balloons. These preliminary results are nevertheless encouraging and we expect that proper optimization of the antenna design will provide ample performance margin for the Titan aerobot.

The third experimental area consists of flight test experiments on Earth using a commercial airship as a technology testbed. Our testbed is an Airspeed Airships AS 800B that has been outfitted by JPL with an onboard flight computer and sensor suite to enable development and flight testing of software for autonomous operations. This vehicle is shown during take-off in Fig. 7, and its basic performance parameters are listed in Table 5. Note that the computer and sensor suite count against the 16 kg dynamic payload capacity. The aerobot avionics is built around the PC-104+ computer architecture. It is composed of a CPU board running the onboard avionics software, a serial board interface to the navigation sensors and pan/tilt unit, a timer/counter board for reading pulse width modulated (PWM) signals from a human safety pilot and generating PWM signals based upon control surface commands from the avionics software, and an IEEE 1394 board for sending commands to, and reading image data from, the navigation and science cameras. The navigation sensors consist of an IMU (angular rates, linear accelerations), a compass/inclinometer (yaw, roll and pitch angles), GPS (absolute 3D position), with future additions scheduled to include a laser altimeter (surface relative altitude), barometric altimeter (absolute altitude against reference point), and ultrasonic anemometer (3D wind speed). The vision sensors consist of two down-looking navigation cameras (to gather imagery used for motion and position estimates that feed into the navigation software) and a science camera (mounted on the pan/tilt unit that acquires imagery used for science-based processing).

Several flights have been conducted to date in the Mojave desert of southern California. Most of these flights have utilized teleoperated control with some brief segments of autonomous control in one or more vehicle axes. A more detailed discussion of this testbed and its preliminary experimental results can be found in Elfes et al (2003). This work is ongoing with fully autonomous flight tests scheduled for the summer and fall of 2004.

Fig. 7: JPL Aerobot Testbed at take-off

Table 5: Aerobot Testbed Parameters

Parameter	Value
Length	11 m
Max. diameter	2.5 m
Hull volume	34 m^3
Static payload (asl)	10 kg
Dynamic payload (asl)	16 kg
Max. ceiling	500 m
Max. speed	44 km/hr
Max. endurance	1 hour
No. of engines	2
Engine power (each)	2.2 kW

5. Conclusions

This paper has presented the design plus selected component-level test results of a Titan aerobot intended for long duration exploration over widely separated points on the world. The technological maturity of components and subsystems ranges from low to moderate; nevertheless no show stoppers have been found to prevent implementation of the basic design. Ongoing development activities are steadily improving the technological readiness of this vehicle concept in the key areas of cryogenic balloon materials, autonomy technology, aerial deployment and inflation, thermo-mechanical design, vehicle prototype construction and testing. With sufficient resources, is anticipated that a Titan aerobot based on this design approach could be ready for launch by the end of the current decade.

6. Acknowledgements

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7. References

Campbell, D. B., G. J. Black, L. M. Carter & S. J. Ostro, "Radar Evidence for Liquid Surfaces on Titan," *Science*, 302, pp 431-434, 2003.

Curtiss Jr., H. C., Hazen D. C. and Putman, W. F., "LTA Aerodynamic Data Revisited," AIAA Paper 75-951, 1975.

Elfes, A., Hall, J. L., Montgomery, J. F., Bergh, C. F., and Dudik, B. A., "Toward a Substantially Autonomous Aerobot for Titan Exploration," AIAA Paper 2003-6714, 2003.

Griffith, C. A., Owen, T., Geballe, T. R., Rayner, J. and Rannou, P., "Evidence for the Exposure of Water Ice on Titan's Surface," *Science*, Vol 300, Issue 5619, 628-630, 25 April 2003.

Hall, Jeffery L., Kerzhanovich, Viktor V., Jones, Jack A., Cutts, James A., Yavrouian, Andre A., Colozza, Antony and Lorenz, Ralph D., "Titan Airship Explorer," Paper #215 presented at the 2002 IEEE Aerospace Conference, Big Sky, MT, March 9-16, 2002.

Jones, Jack A., Wu, Jiunn Jeng, Bachelder Aaron, and Pauken, Michael, "Titan Amphibious Aerover," AIAA Paper 2000-5273, 2000.

Lockwood, M. K. "Titan Aerocapture Systems Analysis," AIAA Paper 2003-4799, July 2003.

Lorenz, R.D. "Post-Cassini Exploration of Titan: Science Rationale and Mission Concepts," Journal of the British Interplanetary Society, Vol 53, pp. 218-234, 2000.

Lorenz, R. D., "Scaling Laws for Flight Power of Airships, Airplanes and Helicopters: Application to Planetary Exploration," Journal of Aircraft, Vol. 38, pp. 208-214, 2001.

Lorenz, Ralph D., "Navigation of Aerial Platforms on Titan," Paper AAS 02-141, AAS/AIAA Space Flight Mechanics Meeting, San Antonio TX, January 27-30, 2002 (a)

Lorenz, Ralph D., private communication, 2002(b).

Solar System Exploration Survey Committee, Space Studies Board, Division of Engineering and Physical Sciences, National Research Council, National Academies Press, Washington D.C., *New Frontiers in the Solar System: An integrated exploration strategy*, 2003.

Yelle, R. V., Strobell, D. F., Lellouch, E. and Gautier, D., "Engineering Models for Titan's Atmosphere," pp. 243-256, in *Huygens: Science Payload and Mission*, ESA-SP 1177, 1997.