TITAN AERIAL EXPLORER (TAE): EXPLORING TITAN BY BALLOON*

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ABSTRACT

Titan Aerial Explorer (TAE) is a mission concept for the exploration of Titan through use of a helium superpressure balloon. The 4.6 m diameter spherical balloon would cruise at a nominal altitude of 8 km just south of the equator and travel around the planet carried by the prevailing wind. The mission science floor is accomplished with a 3 month navigation, with a goal of complete circumnavigation that, at an estimated speed of 1 m/s, would require 6 months. The total floating mass is estimated to be 170 kg (including design margin and helium gas) of which 19 kg is science instruments carried in the gondola suspended below the balloon. The TAE mission would acquire in situ measurements of Titan's troposphere and conduct imaging and sounding of the surface and subsurface at high resolution. The instrument suite would consist of three remote sensors—a camera (VISTA-B), near-infrared spectrometer (BSS) and radar sounder (TRS)—and three in situ experiments—an aerosol collector and analyzer (TCAA), meteorology package (ASI/MET), and a device for measuring electric and magnetic fields and conductivity (TEEP-B). In addition, tracking of the balloon's radio signals would allow for determination of atmospheric circulation patterns at the cruising altitude. Collectively, these measurements would address the two scientific goals of the mission: (1) to explore how Titan functions as a system in the context of the complex interplay of the geology, hydrology, meteorology and aeronomy present there; and (2) to understand the nature of Titan's organic chemistry in the atmosphere and on the surface. Delivery of the balloon and gondola into the atmosphere would be via a Huygens-like entry system with a 3 m diameter aeroshell that is itself released from a carrier spacecraft after a several year interplanetary trip. The balloon would be

aerially deployed and inflated while under parachute descent. The helium inflation gas would be carried in a set of high pressure storage tanks mounted inside the aeroshell. The vehicle would require 240 W of electrical power, potentially supplied by two Advanced Stirling Radioisotope Generators (ASRG) mounted on the gondola. The gondola interior would be kept warm at a temperature near 20 °C, likely aided by use of waste heat from the radioisotope power source. Direct-to-Earth telecommunications would be provided by a 20 W X-band transmitter and a 0.75 m diameter steerable high gain antenna mounted on the gondola. It is estimated that an average of 170 Mbits of data would be transmitted to Earth during each Titan sol using ESA and/or NASA 35/34 m ground antennas. The balloon would be fabricated from a polyester film and fabric laminate. A vent valve and a few kilograms of ballast would be carried to enable a limited number of altitude excursions during the mission. Otherwise, the superpressure design will result in constant altitude flight with very small deviations of tens of meters from the nominal 8 km float altitude.

INTRODUCTION

Suggestions for the use of balloons to explore Titan date at least to the mid-1970s.[1,2] A large number of exploration concepts have been developed since that time, catalyzed by the scientific discoveries resulting from the Voyager 1 flyby in 1980 and the Cassini-Huygens mission that arrived in 2004.[3,4] The results from Cassini-Huygens in particular revealed Titan to be a complex and fascinating world with diverse topographical features and a methane-based hydrological cycle. The motivation to return to Titan for further exploration only intensified in the wake of these results, with increasingly widespread recognition that a buoyant vehicle could provide an outstanding means of *in situ* exploration on a global scale (e.g., Ref. 5). The Huygens probe also measured low winds speeds (< 1-2 m/s) and excellent visibility below a 10 km altitude. These two key results cemented Titan's status as an extremely well-suited flight environment for buoyant vehicles, complementing the previously known favorable aspects of dense, high molecular weight atmospheric gas, very small diurnal temperature variations and low gravity.

The Titan Aerial Explorer (TAE) concept was developed in response to the 2010 ESA Cosmic Visions solicitation for a medium-class space mission. The fundamental approach was to formulate the simplest and least expensive Titan balloon mission that nevertheless enabled an outstanding scientific return. The presumption was that only this least-expensive approach could yield a Titan balloon mission consistent with a medium-class mission cost posture. This paper summarizes the proposed concept including the mission architecture, scientific objectives and instruments, balloon design and rationale, spacecraft design and mission design.

MISSION ARCHITECTURE

The TAE mission architecture is based on a set of design choices that provide for an outstanding science return while minimizing mission cost. The key elements are:

- Minimum of 3 months of balloon flight, with a desire for 6 months which would be required to accomplish one circumnavigation of Titan at a near-equatorial latitude.

- A balloon flight altitude of 8 km, with a preference for doing one or more altitude excursions down the surface.
- Wind-driven balloon trajectory starting near the Huygens landing site. (Huygens site over flight is desired but not essential.)
- Direct-to-Earth telecommunications from the balloon to avoid the need for a relay orbiter.
- A total mission data return of ~ 1 Gbit.

The rest of the mission design and science return flows from these five basic architecture elements. The most notable consequences are:

- Radioisotope power would likely be required for a mission of such a long duration and high data return.
- The balloon does not require onboard propulsion or an autopilot to control its trajectory.
- The balloon does not collect surface samples or otherwise touch the surface.
- A high gain antenna is required on the balloon gondola to provide a sufficient data return rate back to Earth ground antennas.
- The spacecraft consists of an entry vehicle mounted on a carrier spacecraft. The entry vehicle contains the balloon, scientific payload and support systems.
- The balloon deploys and inflates upon arrival at Titan during the initial parachute descent phase.
- Science investigations are limited to what can be achieved from a single balloon platform that does not acquire surface material.

As will be seen in the next section, this science limitation nevertheless allows for a very rich scientific return over the 3-6 month mission duration.

SCIENTIFIC OBJECTIVES AND INSTRUMENTS

TAE science is organized around two themes, which emphasize the special nature of Titan and at the same time its important connections to studies of other planets and the Earth. These themes are:

1. The presence of an atmosphere and liquid volatile “hydrologic” cycle, which implies climate evolution through time.
2. Organic chemistry, which is pervasive through its atmosphere, surface, and probably interior.

Each of these themes is associated with a TAE science goal:

Goal 1: Explore how Titan functions as a system in the context of the complex interplay of the geology, hydrology, meteorology, and aeronomy present there.

Goal 2: Understand the nature of Titan’s organic chemistry in the atmosphere and on its surface.

These goals in turn lead to a set of five primary science objectives for the balloon-borne system, which can then, through the science investigations that devolve from them, be addressed through a set of measurement objectives. Table 1 lists the five science objectives and their associated measurement objectives.

Table 1: TAE Science Goals and Measurements

	Science Objective	Measurements
A	Determine the composition and transport of volatiles and aerosol particles in clouds, including hydrocarbons and nitriles, in order to understand the hydrocarbon cycle. Determine the climatological and meteorological variations of temperature, clouds and winds. (Science Goals 1 and 2)	• Assess surface volatile inventory: $\lambda/\Delta\lambda$ ~1000 over 5–6 microns • Obtain temperature and methane relative humidity soundings over a large swath of Titan's atmosphere (ΔT = 0.1 K; Δx_{CH4} = 0.01) • Perform direct measurement of zonal and meridional winds • Determine cloud distribution, morphology, and extent of supersaturation near the cloud base. • Detect the presence of turbulence and fluctuating electric fields associated with moist convective activity and other meteorological phenomena. • Detect cloud condensates and determine their physical state (solid, liquid) and the presence or absence of nucleating aerosols.
B	Characterize and assess the relative importance today and throughout time of Titan's geomorphologic processes: cryovolcanic, aeolian, tectonic, fluvial, lacustrine, impact and erosional. (Science Goal 1)	• Detect indicators of methane outgassing with spatial resolution 50 m or better • Measure local topographic variations distributed over a broad swath of Titan's surface (50 meter spatial resolution stereo images) • Assess regional morphology and texture; spectral reflectance $\lambda/\Delta\lambda$~1000. • Determine local-scale morphology over selected areas (meter-scale) • Determine subsurface structure in selected areas with penetration depths of at least 100 meters • Map topographic boundaries previously identified by, and at much higher resolution than, Cassini RADAR.
C	Determine internal differentiation and thermal evolution of Titan. Determine if Titan has an internal ammonia-water ocean, a metal core and an intrinsic or induced magnetic field, as well as the extent and origin of geodynamic activity. (Science Goal 1)	• Measure vector magnetic field at low altitude along a large swath of Titan's surface • Measure electric fields to test for the presence of a conducting boundary deep below the surface (i.e., an ammonia-water ocean)
D	Determine geochemical constraints on bulk composition, the delivery of nitrogen and methane and exchange of surface materials with the interior. (Science Goal 1)	• Seek evidence for release of volatiles such as methane and carbon dioxide from surface vents. • Determine spectroscopic composition of oxygen-bearing organics in geologically unusual sites
E	Determine the chemical pathways leading to formation of complex organics in Titan's atmosphere and their modification and deposition on the surface with particular emphasis on ascertaining the extent of organic chemical evolution on Titan. (Science Goal 2)	• Determine surface composition of major hydrocarbons • Measure the bulk composition of particulates in cloud particles

TAE has identified a suite of 6 instruments that can obtain the measurements described in Table 1. These instruments are listed in Table 2 along with estimated mass and power requirements derived from existing or similar devices. Note that TAE can make significant observations of the surface despite never touching it through use of the high resolution camera (VISTA-B), Balloon Slit Spectrometer (BSS) and the Titan Radar Sounder (TRS). The other three instruments provide detailed measurements of key atmospheric properties: Atmospheric

Table 2: TAE Instruments

	Mass (kg)	Peak Power (W)	TRL Level	Approx. Data Rate (Mb/Titan Sol)	Science Contribution
VISTA-B Visible Imaging System for Titan Aerostat-Balloon	2	5	7	108.5	Detailed geomorphology at 10 m resolution and higher in selected areas
BSS—Balloon Slit Spectrometer 4.6–5.6 μm	2.5	9 (11 with shutter)	6	3.5	Mapping organics in concert with surface images
ASI/MET – Atmospheric Structure Inst. / Meteorology Pkg.	1.0	3	6	2.7	Record atmosphere characteristics during aerostat cruise
TEEP-B—Titan Electromagnetic Environment Package	0.5	3.5	8	4.9	Measure electric fields (0–10 kHz) in the troposphere and determine connection with weather; search for induced or permanent magnetic field
TRS—Titan Radar Sounder at >150 MHz	8	15	7	28.9	Determine topography (5 m res) and depth of the ice layer, and detect shallow reservoirs of hydrocarbons, and better than 10 m resolution stratigraphy of geological features.
TCAA—Titan Cloud and Aerosol Analyzer	0.5	1	5	1.2	Analysis of cloud droplets and embedded aerosols for composition and cloud formation processes
Total	**14.5**			**149.7 Mbit**	**Not all instruments operate simultaneously**
30% Res.	**4.4**				
Total with Res.	**18.9**				

Structure and Meteorology (ASI/MET), Titan Electromagnetic Environment Package (TEEP-B) and Titan Cloud and Aerosol Analyzer (TCAA).

BALLOON DESIGN

The balloon system (Fig. 1) is based upon a 4.6 m diameter spherical helium superpressure balloon that has the characteristic of flying at a constant altitude despite thermal and convective perturbations in the atmosphere, both of which are expected to be small at Titan. Two balloons of this type, at approximately the same size, were successfully deployed and flown at Venus in 1985 as part of the Soviet VEGA mission.[6] Thousands of helium super-pressure balloons have also flown on Earth for periods of up to 2 years. The TAE balloon is sized to carry 170 kg, which equals the CBE payload mass plus a 30% contingency. The material of construction is a polyester film plus fabric laminate with an areal density of 75 g/m^2. This material was previously tested under cryogenic conditions and found to have good mechanical properties down to 77 K.[7]

There are two phases for balloon operation upon arrival at Titan: the entry, deployment and inflation (EDI) phase and the science operational phase. The EDI phase (Fig. 2) includes deployment from the aeroshell and then inflation to achieve the aerial flight configuration in the planetary atmosphere. This phase would last for approximately 10 to 20 minutes. The TAE implementation of EDI parallels that used by the VEGA mission at Venus. The science operational phase of the mission flight initiates when the aerostat reaches its stable altitude (~8 km) and continues through the collection of scientific data over a 3 to 6 month period.

The release phase requires a set of auxiliary components in addition to the balloon:

- A container for long duration storage of the folded balloon envelope.
- High pressure tanks filled with helium, and plumbing (valves, pipes) for balloon inflation.
- A set of pyrotechnically actuated cutters and valves to perform release actions and control the flow of helium gas.
- A computer and sensors to control the sequence of events.

The release phase begins after atmospheric entry and descent to a 9 km altitude. A small parachute (20 m^2) is required to provide a 5 m/s descent speed which provides a sufficiently low dynamic pressure (50 Pa) on the deploying balloon. The flow of helium gas starts soon after the deployment of the balloon envelope from its storage container, and continues for 10–20 minutes, delivering 28 kg of helium into the balloon. When finished, the parachute and inflation system are detached and the balloon and its payload ascend to the float altitude. The balloon is designed to

Fig. 1: Artists concept of the TAE Balloon and gondola.

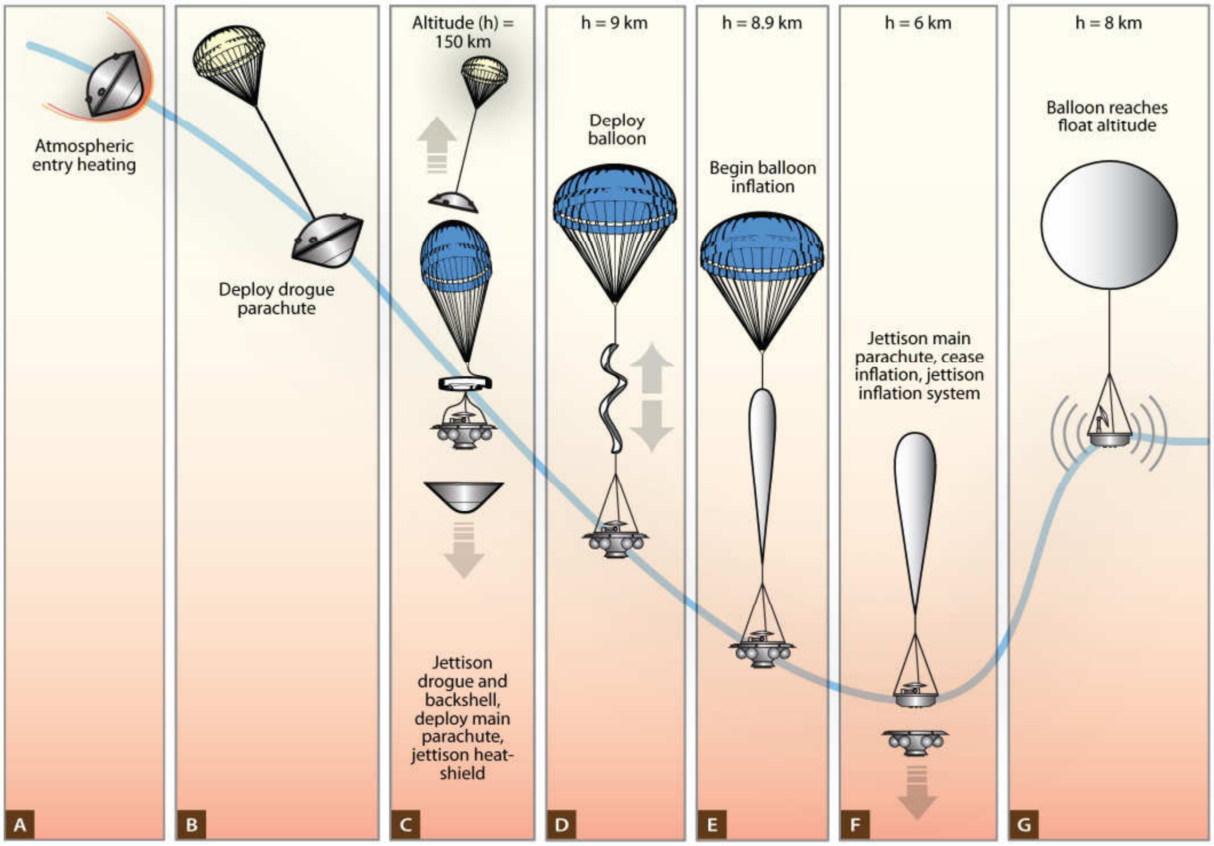

Fig. 2: Entry, Deployment and Inflation (EDI) Sequence.

pressurize to 1000 Pa upon reaching 8 km and stabilize at that altitude.

The 85 K cryogenic environment will ensure that negligible amounts of helium will be lost by diffusion through the balloon material during the science phase. Balloon float lifetime will therefore be limited only by leakage through pinhole defects. Analysis shows that the 3 month science mission requirement can be achieved even with 20 pinholes of size 10 microns in diameter (Fig. 3). The corresponding leak rate of ~1 g/day is so small that very affordable amounts of ballast (6 g/day) could extend the lifetime to 6 months under these leakage conditions. Future prototype construction and testing will be required to quantify the achievable leakage rates and resultant actual lifetimes as a function of ballast carried.

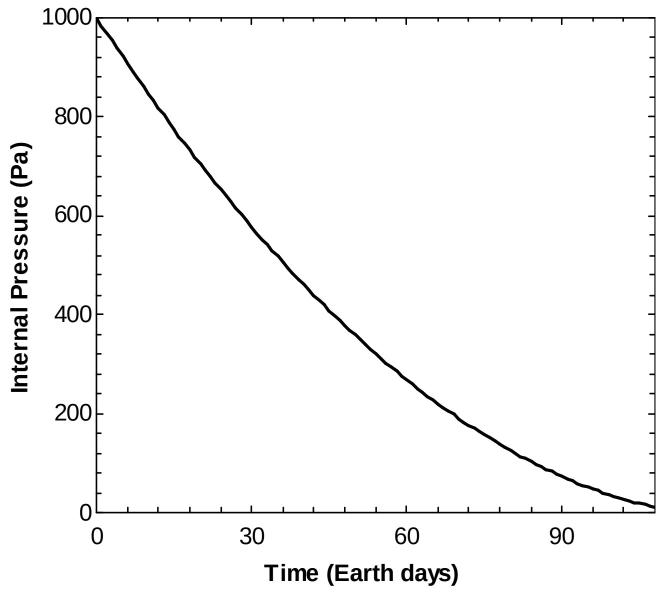

Fig. 3: Leakage calculation showing 3 month (90 day) lifetime even with 20 pinholes of 10 micron diameter.

One limitation of a superpressure balloon is that although its inherent altitude stability is ideal for long duration flight, it does inhibit altitude excursions for science investigations. TAE solves this problem by employing traditional gas venting and ballast drops towards the end of the mission to effect several altitude excursions. Gas venting may not be required for the first descent if the basic leakage rate has already de-pressurized the balloon, but use of a valve allows for more than one profile and gives control over the timing of all desired descents.

It is important to note that the use of a hot air, or Montgolfiere, balloon was seriously considered for TAE. Titan Montgolfiere balloons achieve buoyancy by heating up ambient atmosphere inside the balloon using waste heat from the radioisotope power source. This concept was used by the TSSM flagship mission concept in 2008 because of its insensitivity to leakage and hence ability to support very long mission durations of a year or more.[5] Hot air balloons are buoyancy modulated by opening and closing a valve that sits at the apex of the balloon. When open, warm air vents to the outside, buoyancy decreases and the balloon descends. Conversely, when the valve is closed, the internal temperature rises, buoyancy increases and the balloon ascends. This control method requires only a little power to actuate the valve and can be repeated as many times as is needed, thereby providing an essentially unlimited number of altitude excursions. Set against these advantages, however, is the fact that Titan hot air balloons are less technologically mature than Titan helium balloons. The chief uncertainty is the thermodynamic performance of the hot air balloon, particularly under transient conditions with significant forced convection, as is the case with the initial inflation of the balloon. While these uncertainties can be mitigated with a dedicated analysis and test program, they ran counter to the stated preference for high maturity technology in the Cosmic Visions solicitation to which TAE was directed. The decision was therefore made to go with a helium superpressure balloon on TAE, understanding full well that future versions of TAE will revisit the choice of hot air versus helium buoyancy provision in light of future technology development progress.

SPACECRAFT DESIGN

The Titan Aerial Explorer would be built around the two main elements illustrated in Fig. 4:

- The Carrier Module (CM)
- The Descent Module (DM)

The CM plus DM assembly constitutes the composite spacecraft. The separation of the two modules will occur a few days to a few hours before the atmospheric entry of the DM, when the error budget on the entry ellipse is consistent with the targeted coordinates for the aerial mission start. The DM comprises the Entry, Descent and Inflation System (EDI) and the Aerostat. The Aerostat includes the balloon system, the gondola, where the scientific instruments reside, and a proposed Advanced Stirling Radioisotope Generator (ASRG) power system.

The carrier is a three-axis controlled spacecraft that nevertheless will spend much of its interplanetary cruise in a passive spin-stabilized mode to conserve fuel. It has a bi-propellant propulsion system with 2 sets of 8 attitude control thrusters and a 400 N main engine for execution of deep space maneuvers. Electrical power could be provided by two ASRGs that would provide ~120 W each at the end of mission. This power system is located on the DM but will be shared by the CM during the cruise phase of the mission. Similarly, the command and data handling functions of the DM and CM are supplied by a single unit located on the DM. Telecommunications is provided by an X-band system with redundant 35 W travelling wave tube amplifiers (TWTAs), a steerable 2.2 m high gain antenna (HGA) and three low gain antennas. The nominal data transfer rates at Titan are 4 kbps downlink and 256 bps uplink.

The Descent Module (Fig. 5) is a 3 m diameter sphere-cone aeroshell containing the balloon, gondola, parachutes and helium inflation system. In shape (60° cone angle) and size (3 vs 2.6 m) it is similar to the Huygens aeroshell and will experience comparable aerodynamic heating (1.5 MW/m^2). The EDI sequence is described above in the previous section and schematically illustrated in Fig. 2.

The gondola is the heart of TAE. It consists of a single platform, ~1.5 m diameter, with the equipment, payload, and 2 ASRGs located on the bottom side of the platform, and the HGA installed on its upper surface. Its power and processing capabilities are shared with the carrier, the

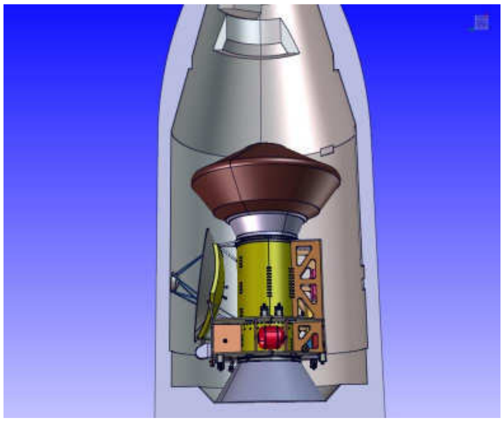

Fig. 4: TAE Carrier and Descent Modules stacked in launch vehicle fairing.

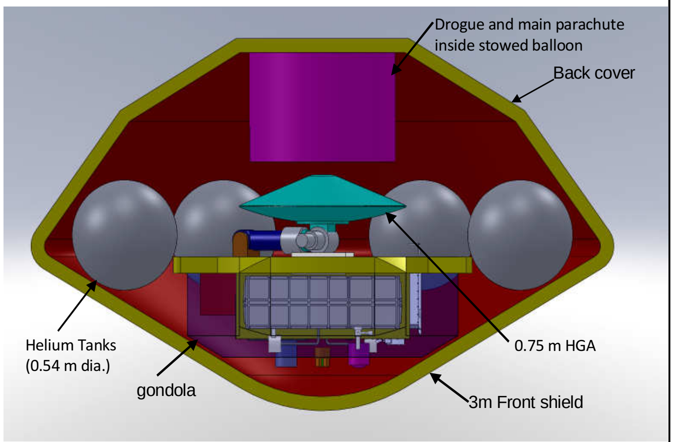

Fig. 5: Descent Module internal layout

EDS and the balloon system to get a fully optimized design from a mass point of view.

The gondola houses a powerful integrated computer responsible for the following functions: command receipt and data handling, power control, thermal control, telecommunication interface, HGA pointing, and payload data collection and commanding. It also provides 32 Gbits of storage capacity to record science and housekeeping data acquired during the Titan night when the vehicle is not visible from the Earth.

Gondola power provided by 2 ASRGs would be able to deliver 120W electrical power each (minimum end-of-life) and waste heat of ~500 W_{th} each. The waste heat would be used for maintaining the thermal balance of the CM during cruise and thermal balance of the gondola equipment while in the cold Titan atmosphere during the balloon flight. Excess heat during cruise would be radiated to deep space using a thermal radiator.

Direct communication with Earth during the TAE balloon mission will be performed by a telecommunications system based on redundant 20 W X-band TWTAs and a steerable 0.75 m diameter HGA. In combination with the ESA 35 m antenna network, this design allows for a downlink rate of 250 bps. This would provide a return link channel capacity of about 173 Mbits over one Titan orbit of Saturn (about 16 days) among which the science payload in the Gondola will be allocated a science data volume of 150 Mbits. The returned science data would amount to 900 Mbits at the end of the 3 month nominal mission. The use of the Russian 64 m or the US/DSN 70 m antennas would enable to increase the overall data return by a factor of ~4. The accurate pointing of the HGA will be achieved by using a set of 6 sun sensors to first locate the Sun, and therefore the Earth within few degrees, and then perform an antenna conical scan to lock on a "beacon" signal transmitted from ground at the beginning of the telecom phase.

In addition, the up-link transmission will facilitate two-way phase transfer calibration for precise Doppler and VLBI tracking. The nominal downlink data rate achievable through the nominal X-band radio system is 250 bps.

The TAE mass budget is summarized in Table 3. The aerostat power budget is summarized in Table 4.

MISSION DESIGN

As proposed to the ESA Cosmic Visions program, TAE would be launched on a Soyuz-Fregat from Kourou on December 21, 2022. TAE would first enter an elliptical orbit at Earth for approximately 1 month and then depart into interplanetary space with a large 1,530 m/s delta-v maneuver using the CM bi-prop propulsion system. The spacecraft would travel for 9.5 years before arriving at Titan after performing two Venus and two Earth gravity assist maneuvers and four deep space propulsion maneuvers en route. Table 5 and Figure 6 summarize the TAE trajectory design.

The maximum possible delivered mass to Titan is 1,428 kg, consistent with the required TAE mass of 1,368 kg as shown in Table 3. The planned entry point at Titan is -10° S and 240° W, close to the Huygens landing site. The computed entry speed is 6.2 km/s at an altitude of 1,270 km above the surface.

Table 3: TAE Mass Budget

Item	CBE	Maturity Margin	Total Mass with Maturity Margin
Carrier Module			
Structure	93.5	20%	112.2
Mechanisms	20	20%	24.0
Thermal	35.8	20%	43.0
Propulsion (dry)	166.44	10%	183.1
AOCS	23.3	10%	25.6
Data handling	0	0%	0.0
X-band telecommunications	50.72	11%	56.4
Power	40.2	7%	43.2
Harness	30.1	20%	36.1
Carrier dry mass	**460.1**	**13.81%**	**523.6**
System margin (20%)	104.7		
Carrier dry mass with 20% system level margin (kg)	**628.3**		
Descent Module			
Aerostat and Helium Storage and Inflation			
Balloon	9.2		
Structure / enclosure	17.0		
Electrical harness	5.5		
Electrical power electronics	3.5		
ASRG	44.0		
C&DH	5.4		
ACS	1.6		
Telecom	20.0		
Thermal	10.0		
6 Instruments	15.0		
Ballast	5.0		
Storage and inflation system (w/ cont.)	206.4		
Contingency (30%)	102.8		
Aerostat + storage & inflation system with 30% system margin	**445.4**		
Entry & Descent System			
Front shield structure	39.5	20%	47.4
TPS	55.6	20%	66.7
Back cover structure	35	20%	42.0
Back cover TPS	30	20%	36.0
Mechanisms	17.4	20%	20.9
Parachute system	27	20%	32.4
EDS mass	204.5	20%	245.4
System margin (20%)	49.1		
EDS mass with 20% system level margin (kg)	**294.5**		
Descent module mass with margin (kg)	**739.9**		
Total TAE dry mass with margin (kg)	**1368.2**		
Maximum arrival dry mass (kg)	**1428.0**		
Additional mass reserve (kg)	**59.8**		

Table 4: TAE Aerostat Power Budget

	Science + Telecom	Science Only	Telecom Only
C&DH	30	30	30
ACS	16	16	16
Telecom	70	15	70
Thermal	4	4	4
Instruments	20	20	0
30% contingency	42.0	25.5	36.0
Sum all users with system margin	**182.0**	**110.5**	**156.0**
EOM ASRG capability (W)	240.0	240.0	240.0
Power margin	**32%**	**117%**	**54%**

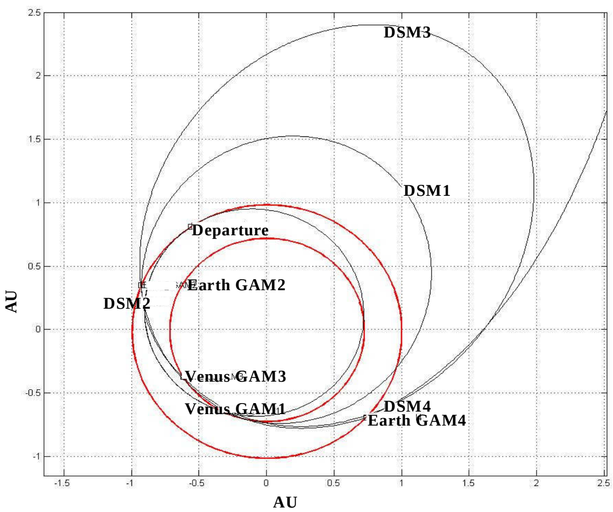

Fig. 6: TAE Interplanetary trajectory

Table 5: Interplanetary Trajectory Parameters

Departure	
Launch date	21/12/2022
Escape date	25/01/2023
Mass after Fregat separation (kg)	3,070
Launcher perf @ escape (kg)	1,853
Escape maneuver (m/s)	1,530
Escape dispersion correction	40
Cruise	
Swing-by 1 Venus	05/02/2024
DSM 1 (m/s)	15
Swing-by 2 Earth	28/02/2025
DSM 2 (m/s)	163
Swing-by 3 Venus	10/04/2025
DSM 3 (m/s)	95
Swing-by 2 Earth	10/08/2027
DSM 4 (m/s), 18/08/2017	408
Navigation (m/s)	40
Attitude control (kg)	40
Arrival	
Arrival date	30/04/2032
Relative arrival velocity (m/s)	6,228
Arrival mass (kg)	1,428
Mission duration (years)	9.3

CONCLUSIONS

The Titan Aerial Explorer (TAE) concept was developed in response to the 2010 ESA Cosmic Visions solicitation for a medium-class space mission. The fundamental approach was to formulate the simplest and least expensive Titan balloon mission that nevertheless enabled an outstanding scientific return. It consists of a 4.6 m diameter spherical helium superpressure balloon that primarily flies at a constant 8 km altitude for a 3 to 6 Earth month mission. A set of six science instruments carried on the balloon gondola would provide for a rich scientific investigation of Titan's atmosphere and surface with an approximate data return of 1 Gbit per Titan sol, or 6 Gbits in the minimum 3 month mission. This data features high resolution imaging, spectroscopic observations and radar sounding of the surface, and various meteorological investigations of the atmosphere. The overall mission concept includes preliminary designs for the interplanetary trajectory, mechanical layout of the spacecraft, and mass and power budgets.

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