The Huygens Probe System Design

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1. Introduction

The Huygens Probe is the ESA-provided element of the joint NASA/ESA Cassini/Huygens mission to Saturn and Titan, the planet's largest moon. The industrial Phase B activities began in January 1991 under the leadership of Aerospatiale, the Huygens prime contractor. The geographical distribution of Huygens work is shown in Fig. 1; the organisation of the industrial consortium is given in Fig. 2.

The Probe will be carried to Titan by the Cassini Saturn Orbiter. Huygens will be dormant during the interplanetary journey of 6.7 years, although it will be activated about every 6 months to verify and monitor its health. It will be released nominally 22 days before the Titan encounter. The Probe's aeroshell will decelerate it in less than 3 min from the entry speed of about 6 km/s to 400 m/s (Mach 1.5) by 150-180 km altitude. From that point onwards, a pre-programmed sequence will trigger parachute deployment and heatshield ejection. The main part of the scientific mission can then start, lasting for the whole descent of 2-2.5 h.

2. The Huygens Model Philosophy

The Huygens model philosophy was optimised to achieve the most complete verification possible that the Probe system meets the mission requirements within the cost envelope and the tight schedule constraints imposed by the launch window. Four models were developed at system level:

1. Structural, Thermal & Pyro Model (STPM): to qualify the Probe design (including all mechanisms activated by pyrotechnic devices) for all structural, mechanical and thermal requirements;
2. Electrical Model (EM): to verify the electrical performances of the Probe and of the electrical/functional interfaces with the Orbiter;
3. Special Model (SM2): used for the balloon drop test in May 1995. All the mechanisms and the descent control systems were flight-standard;
4. Flight Model (FM).

The overall development schedule is shown in Fig. 3, indicating the main milestones and the major Reviews carried out at agency level.

Fig. 1. Geographical distribution of the Huygens Probe industrial responsibility.

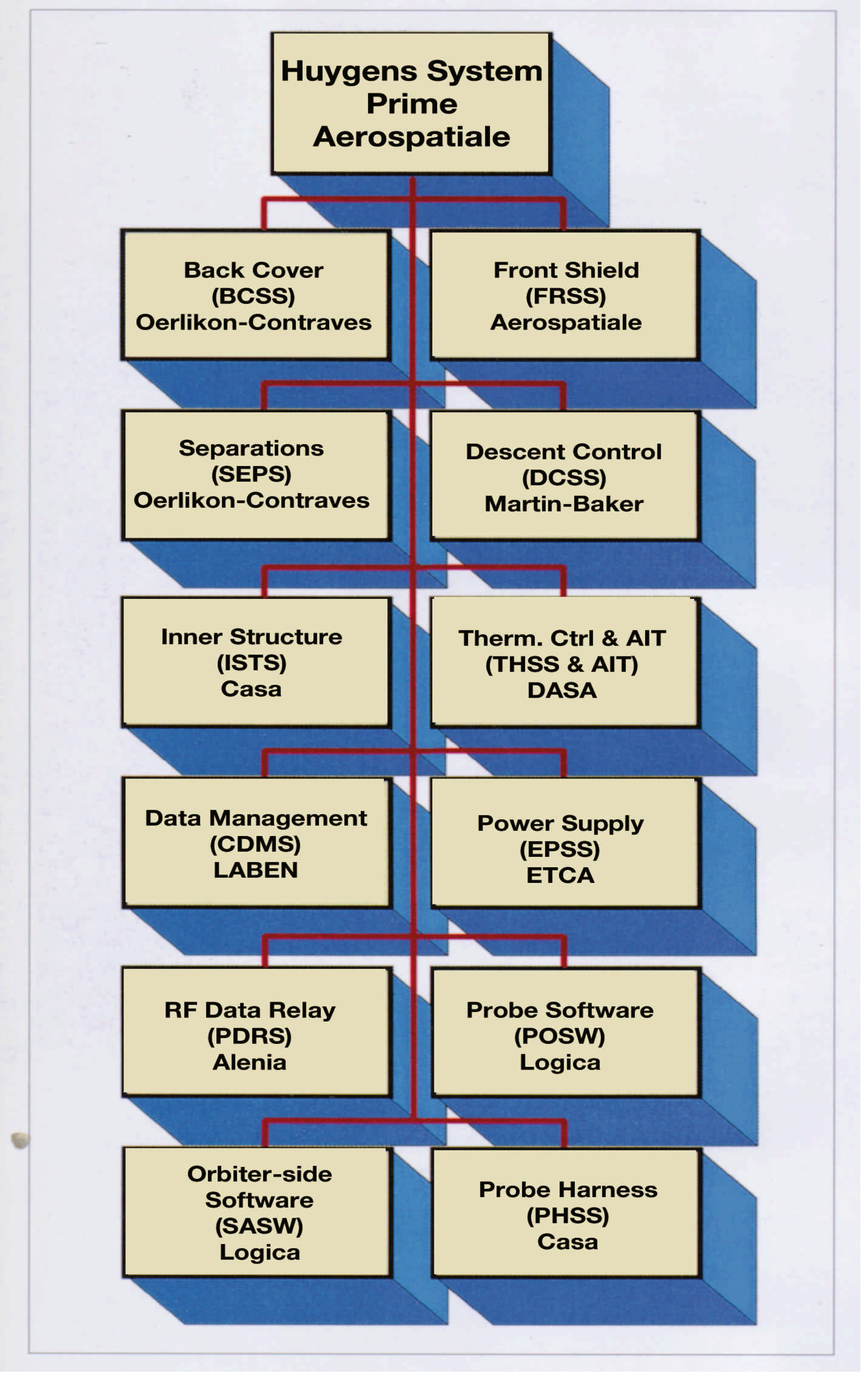


Fig. 2. The organisation of the Huygens industrial consortium.

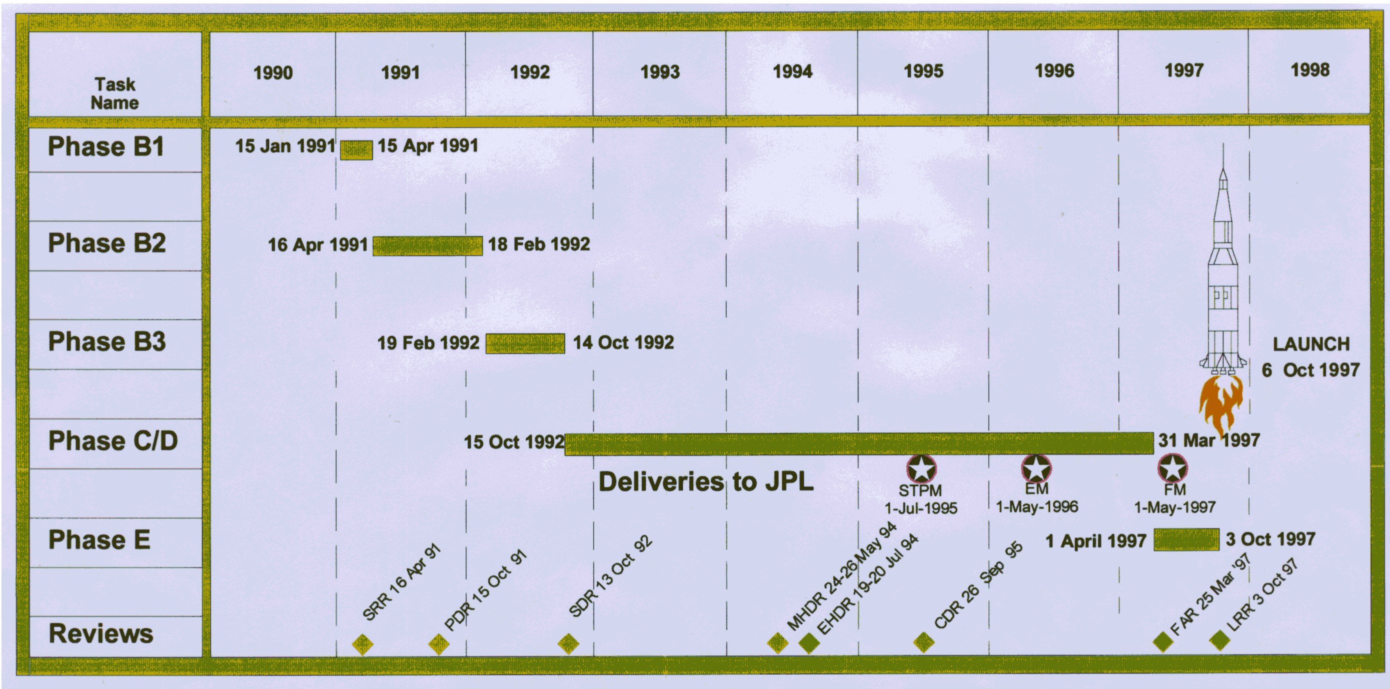


Fig. 3. The Huygens project overall development schedule. SRR: System Requirement Review; PDR: Preliminary Design Review; SDR: System Design Review; MHDR: Mechanical Hardware Design Review; EHDR: Electrical Hardware Design Review; CDR: Critical Design Review; FAR: Flight Acceptance Review; LRR: Launch Readiness Review.

3. Overall Configuration

The Probe System comprises two principal elements:

1. the 318 kg Huygens Probe, which enters Titan's atmosphere after separating from the Saturn Orbiter;
2. the 30 kg Probe Support Equipment (PSE), which remains attached to the Orbiter after Probe separation.

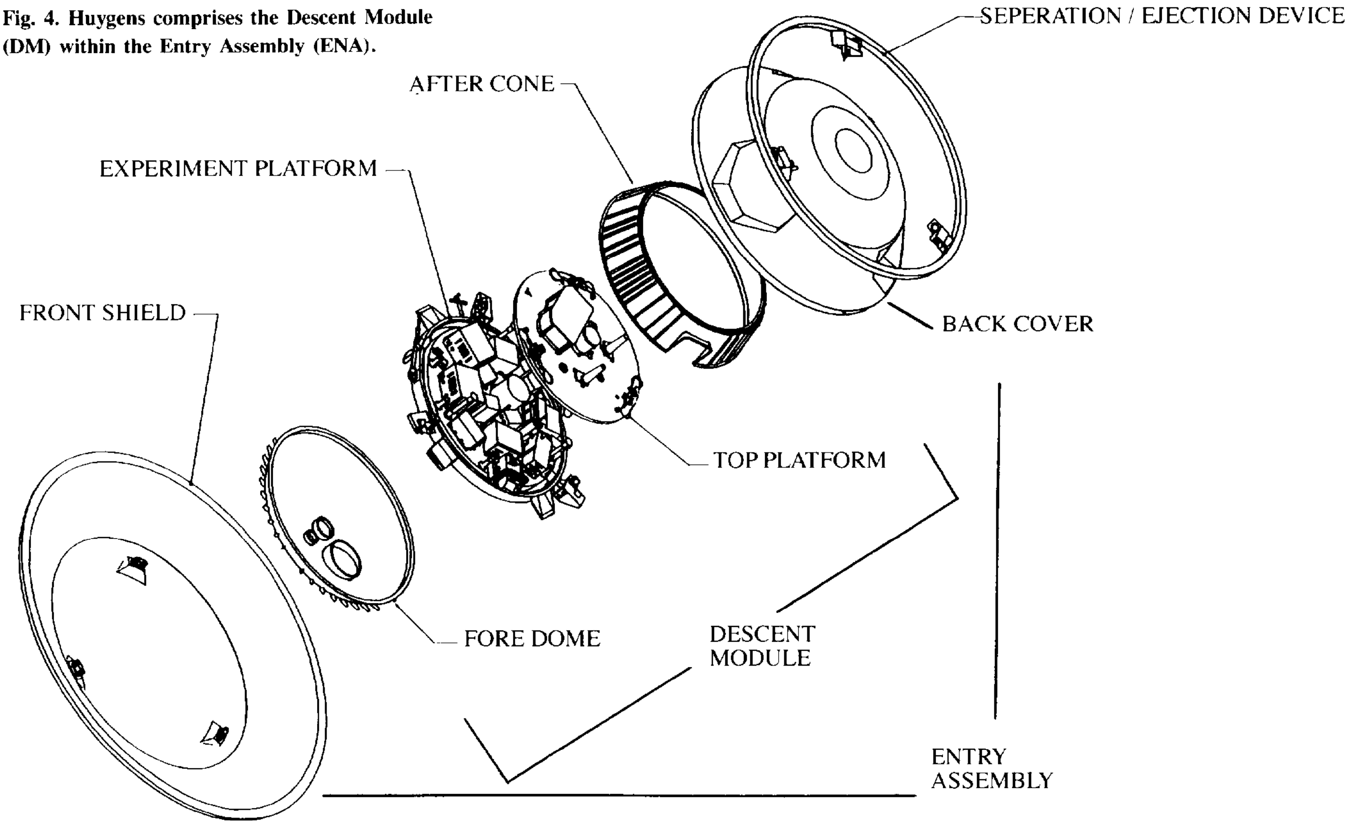
Table 1 provides the mass breakdown. The Probe (Fig. 4) consists of the Entry Assembly (ENA) cocooning the Descent Module (DM). ENA provides Orbiter attachment, umbilical separation and ejection, cruise and entry thermal protection, and entry deceleration control. It is jettisoned after entry, releasing the Descent Module. The DM comprises an aluminium shell and inner structure containing all the experiments and Probe support subsystems, including the parachute descent and spin control devices.

The PSE consists of:

1. four electronic boxes aboard the Orbiter: two Probe Support Avionics (PSA), a Receiver Front End (RFE) and a Receiver Ultra Stable Oscillator (RUSO);
2. the Spin Eject Device (SED);
3. the harness (including the umbilical connector) providing power and RF and data links between the PSA, Probe and Orbiter.

The overall Probe System configuration and its relation to the Orbiter is shown functionally in Fig. 5 and pictorially in Fig. 6. The subsystem breakdown is illustrated in Fig. 7. Each subsystem is described in detail below.

Fig. 4. Huygens comprises the Descent Module (DM) within the Entry Assembly (ENA).



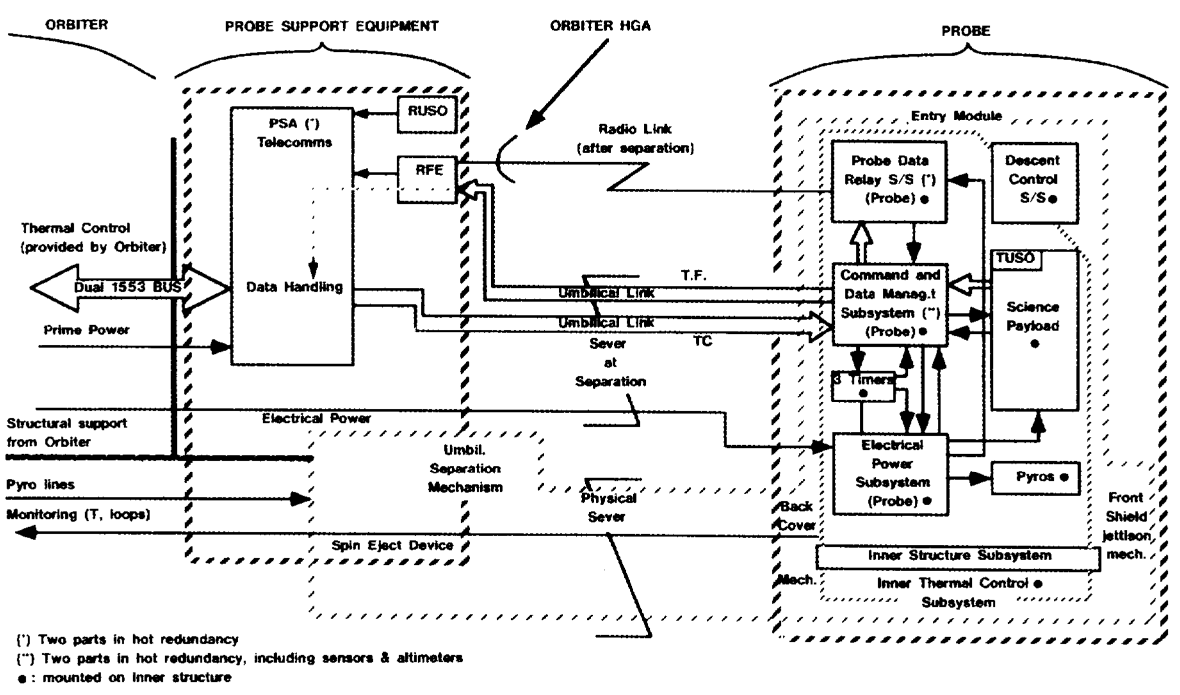


Fig. 5. Huygens Probe System architecture. PSA: Probe System Avionics; S/S: subsystem; TUSO: Transmitter Ultra Stable Oscillator; RUSO: Receiver Ultra Stable Oscillator; HGA: High Gain Antenna; RFE: Receiver Front End; TF: Transfer Frame.

Table 1. Huygens mass budget.

	Probe	PSE
Subsystems		
FRSS	78.75	
BCSS	16.13	
SEPS	11.40	10.29
DCSS	12.13	
ISTS	41.41	
THSS	20.60	1.50
EPSS	44.73	
PHSS	12.61	
CDMS	23.10	
PDRS	6.04	16.30
Experiments		
TUSO/RUSO	1.90	1.90
SSP	4.87	
GCMS	17.20	
HASI	5.77	
DISR	8.07	
DISR cover	3.63	
ACP	6.18	
Fasteners, etc	0.95	
Balance mass	2.85	
Total	**318.32**	**29.99**

PSE: Probe Support Equipment (on Orbiter); FRSS: Front Shield Subsystem; BCSS: Back Cover Subsystem; SEPS: Separation Subsystem; DCSS: Descent Control Subsystem; ISTS: Inner Structure Subsystem; THSS: Thermal Subsystem; EPSS: Electrical Power Subsystem; PHSS: Probe Harness Subsystem; CDMS: Command and Data Management Subsystem; PDRS: Probe Data Relay Subsystem; TUSO/RUSO: Transmitter/Receiver Ultra Stable Oscillator; SSP: Surface Science Package; GCMS: Gas Chromatograph Mass Spectrometer; HASI: Huygens Atmospheric Structure Instrument; DISR: Descent Imager/Spectral Radiometer; ACP: Aerosol Collector and Pyrolyser.

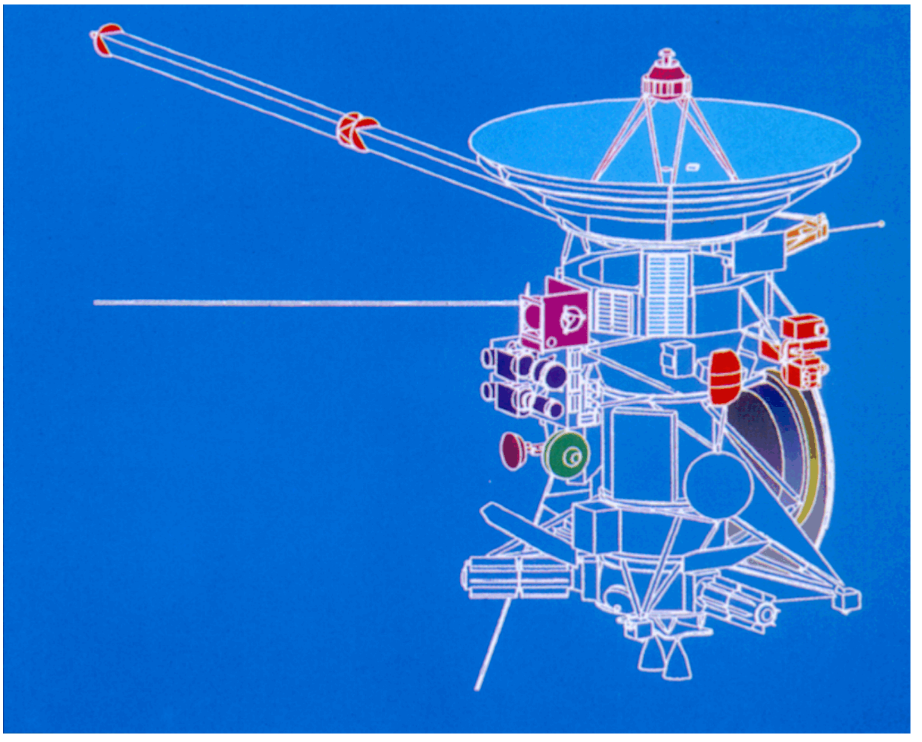


Fig. 6. Huygens Probe accommodation on the Cassini Orbiter.

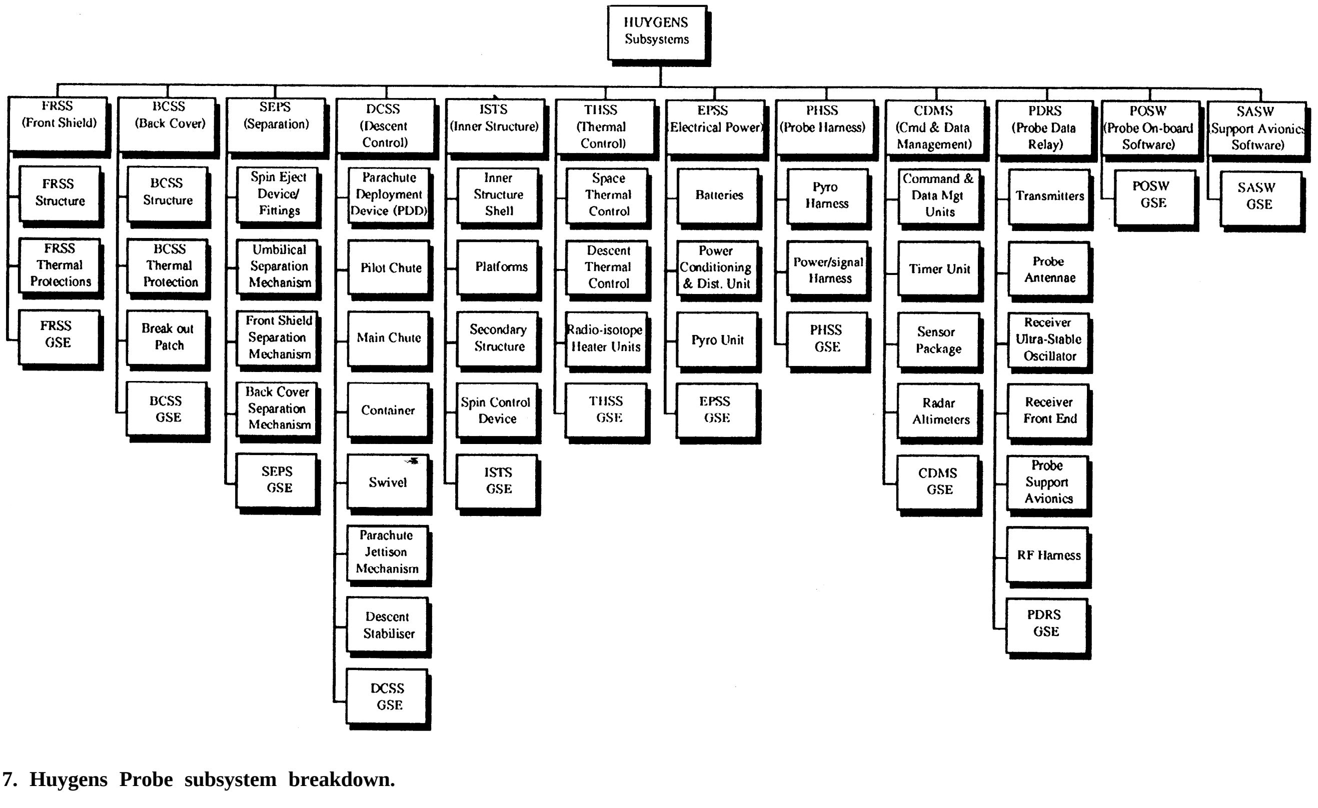


Fig. 7. Huygens Probe subsystem breakdown.

4. Mechanical/Thermal Subsystems

4.1 Front Shield Subsystem (FRSS)

The 79 kg, 2.7 m diameter, 60° half-angle coni-spherical Front Shield will decelerate the Probe in Titan's upper atmosphere from about 6 km/s at entry to a velocity equivalent to about Mach 1.5 by around 160 km altitude. Tiles of AQ60 ablative material, a felt of silica fibres reinforced by phenolic resin, provide protection against the 1 MW/m^2 thermal flux. The shield is then jettisoned and the Descent Control Subsystem (DCSS) is deployed to control the descent of the DM to the surface.

The FRSS supporting structure is a CFRP honeycomb shell which also provides some DM thermal protection during entry. The AQ60 tiles are attached to the CFRP structure by adhesive CAF/730. Prosial, a suspension of hollow silica spheres in silicon elastomer, is sprayed directly on to the aluminium structure of the FRSS rear surfaces, where fluxes are ten times lower.

4.2 Back Cover Subsystem (BCSS)

The Back Cover protects the DM during entry, ensures depressurisation during launch and carries multi-layer insulation (MLI) for the cruise and coast phases. As it does not have stringent aerothermodynamic requirements, it is a stiffened aluminium shell of minimal mass (11.4 kg) protected by Prosial (5 kg). It includes: an access door for late integration and forced-air ground cooling of the Probe; a break-out patch through which the first (drogue) parachute is fired; a labyrinth sealing joint with the Front Shield, providing a non-structural thermal and particulate barrier.

4.3 Descent Control Subsystem (DCSS)

The DCSS controls the descent rate to satisfy the scientific payload's requirements, and the attitude to meet the requirements of the Probe-Orbiter RF data link and of the descent camera's image-taking.

The DCSS is activated nominally at Mach 1.5 and about 160 km altitude. The sequence (Fig. 8) begins by firing the Parachute Deployment Device (PDD) to eject the pilot 'chute pack through the Back Cover's break-out patch, the attachment pins of which shear under the impact. The 2.59 m diameter Disk Gap Band (DGB) pilot 'chute inflates 27 m behind the DM and pulls the Back Cover away from rest of the assembly. As it goes, the Back Cover pulls the 8.30 m diameter DGB main parachute from its container. This canopy inflates during the supersonic phase to decelerate and stabilise the Probe through the transonic region. The Front Shield is released at about Mach 0.6. In fact, the main parachute is sized by the requirement to provide sufficient deceleration to guarantee a positive separation of the Front Shield from the Descent Module.

The main parachute is too large for a nominal descent time shorter than 2.5 h, a constraint imposed by battery limitations, so it is jettisoned and a 3.03 m diameter DGB stabilising parachute is deployed. All parachutes are made of Kevlar lines and nylon fabric. The main and stabiliser 'chutes are housed in a single canister on the DM's top platform. Compatibility with the Probe's spin is ensured by incorporating a swivel using redundant low-friction bearings in the connecting riser of both the main and stabiliser 'chutes.

4.4 Separation Subsystem (SEPS)

SEPS provides: mechanical and electrical attachment to, and separation from, the Orbiter; the transition between the entry configuration ('cocoon') and the descent configuration (DM under parachute). The three SEPS mechanisms are connected on one side to Huygens' Inner Structure (ISTS) and on the other to the Orbiter's supporting struts. As well as being the Probe-Orbiter structural load path, each SEPS fitting incorporates a pyronut for Probe-Orbiter separation, a rod cutter for Front Shield release and a rod cutter for Back Cover release.

Within SEPS, the Spin Eject Device (SED) performs the mechanical separation from the Orbiter:

- three stainless steel springs provide the separation force
- three guide devices, each with two axial rollers running along a T-profile helical track, ensure controlled ejection and spin, even in degraded cases such as high friction or a weak spring
- a carbon fibre ring accommodates the asymmetrical loads from the Orbiter truss and provides the necessary stiffness before and after separation
- three pyronuts provide the mechanical link before separation.

In addition, the Umbilical Separation Mechanism of three 19-pin connectors, which provide Orbiter-Probe electrical links, is disconnected by the SED.

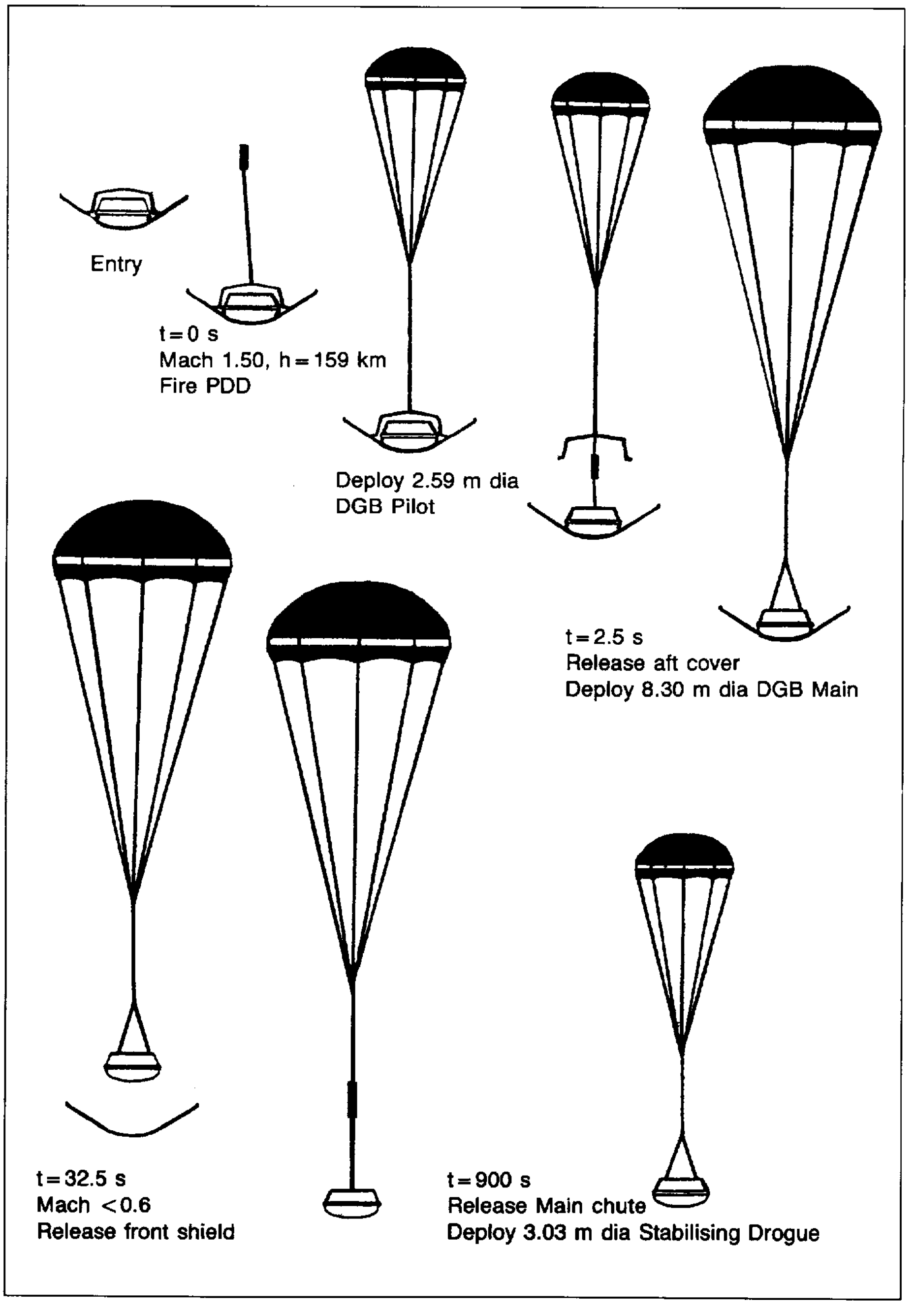


Fig. 8. Huygens parachute deployment sequence.

4.5 Inner Structure Subsystem (ISTS)

The ISTS provides mounting support for the Probe's payload and subsystems. It is fully sealed except for a vent hole of about 6 cm^2 on the top, and comprises:

- the 73 mm thick aluminium honeycomb sandwich Experiment Platform; supports the majority of the experiments and subsystems units, together with their associated harness
- the 25 mm thick aluminium honeycomb sandwich Top Platform; supports the Descent Control Subsystem and Probe RF antennas, and forms the DM's top external surface
- the After Cone and Fore Dome aluminium shells, linked by a central ring
- three radial titanium struts; interface with SEPS and ensure thermal decoupling, while three vertical titanium struts link the two platforms and transfer the main parachute deployment loads
- 36 spin vanes on the Fore Dome's periphery; provide spin control during descent
- the secondary structure; for mounting experiments and equipment.

4.6 Thermal Subsystem (THSS)

While the PSE is thermally controlled by the Orbiter, the Probe's THSS must maintain all experiments and subsystem units within their allowed temperature ranges during all mission phases. In space, the THSS partially insulates the Probe from the Orbiter and ensures only small variations in the Probe's internal temperatures, despite the incident solar flux varying from 3800 W/m^2 (near Venus) to 17 W/m^2 (approaching Titan after 22 days of the coast phase following Orbiter separation).

As shown in Fig. 9, Probe thermal control is achieved by:

- MLI surrounding all external areas, except for the small 'thermal window' (see below) of the Front Shield
- 35 Radioisotope Heater Units (RHUs) on the Experiment and Top Platforms continuously providing about 1 W each even when the Probe is dormant
- a white-painted 0.17 m^2 thin aluminium sheet on the Front Shield's forward face acting as a controlled heat leak (about 8 W during cruise) to reduce sensitivity of thermal performances to MLI efficiency.

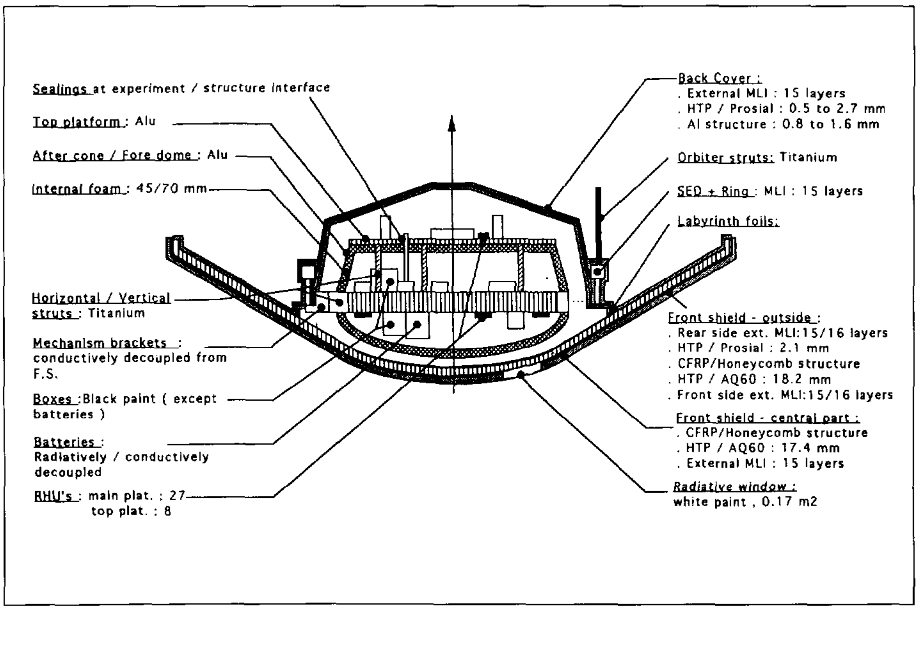


Fig. 9. The Probe's thermal control system. RHU: Radioisotope Heater Unit; MLI: Multi Layer Insulation.

The MLI is burned and torn away during entry, leaving temperature control to the AQ60 high-temperature tiles on the Front Shield's front face, and to Prosial on the Front Shield's aft surface and on the Back Cover.

During the descent phase, thermal control is provided by foam insulation and gas-tight seals. Lightweight open-cell Basotect foam covers the internal walls of DM's shells and Top Platform. This prevents convection cooling by Titan's cold atmosphere (70 K at 45 km altitude) and thermally decouples the units mounted on the Experiment Platform from the cold aluminium shells. Gas-tight seals around all elements protruding through the DM's shell minimise gas influx. In fact, the DM is gas tight except for a single 6 cm^2 hole in Top Platform that equalises pressure during launch and descent to Titan's surface.

5. Electrical Power Subsystem (EPSS)

5.1 Description

Utilisation of the available battery energy during the mission is detailed in Table 2. As shown in Fig. 10, the EPSS consists of:

Five batteries Provide mission power from Orbiter separation until at least 30 min after arrival on Titan's surface. Each battery comprises two modules of 13 $LiSO_2$ (7.6 Ah) cells in series.

Power Conditioning & Distribution Unit (PCDU) Provides the power conditioning and distribution to the Probe's equipment and experiments via a regulated main bus, with protection to ensure uninterrupted operations even in the event of single failure inside or outside the PCDU.

Table 2. Huygens nominal battery energy budget.

	Coast (22 days) (W)	Pre-entry & entry (18 min) (W)	Descent w/o proximity sensing (80 min) (W)	Descent with proximity sensing (73 min) (W)	**Energy** (Wh)
PDRS (on Probe)		10.98	82.61	82.61	214
CDMS	0.272	26.39	26.39	37.73	246
EPSS (incl. Pyro)		1.65	1.65	1.65	5
Payload		60	180	180	325
PCDU losses		25	47.3	47.3	128
Harness losses (0.5%)		0.50	1.45	1.51	4
Power total	**0.272**	**125**	**339**	**351**	
Pre-separation checks					50
Required Energy (nominal)					**972**
Failures assumed: single Probe unit fails ON					85
single experiment fails ON					110
Required Energy (assuming failed units)					**1167**
Available Energy (assuming failed batteries)					**1184**
Energy loss due to assumed battery failures: 1 string (of 10) failed; 1 cell (of 5) in each string failed					355
Worst-case energy loss due to 7-year storage					520
NOMINAL BATTERY CAPACITY (5 fresh batteries)					**2059**

PDRS: Probe Data Relay System; CDMS: Command and Data Management System; EPSS: Electrical Power Subsystem; PCDU: Power Conditioning and Distribution System

During the cruise phase, the Probe is powered by the Orbiter and the PCDU isolates the batteries. The five interface circuits connected to the Orbiter's Solid State Power Switches (SSPSs) provide Probe-Orbiter insulation and voltage adaptation between the SSPS output and the input of the PCDU's Battery Discharge Regulator (BDR) circuits. The BDRs condition the power from either the Orbiter or the batteries and generate the 28 V bus, controlled by a centralised Main Error Amplifier (MEA). The distribution is performed by active current limiters, with the current limitation adapted for each user and with ON/OFF switching capability.

The Mission Timer, however, is supplied by three switchable battery voltage lines through series fuses or, when the PCDU is powered by the Orbiter, by dedicated output voltage lines of the Orbiter interface circuits.

The PCDU also provides a protected +5 V supply used by the Pyro unit to generate the bi-level status telemetry of the selection relays and for the activation circuit that switches ON the Pyro unit's energy intercept relay.

Pyro Unit (PYRO) Provides two redundant sets of 13 pyro lines, directly connected to the centre taps of two batteries (through protection devices), for activating pyro devices. Safety requirements are met by three independent levels of control relays in series in the Pyro Unit, as well as active switches and current limiters controlling the firing current (Fig. 11). The three series relay levels are: energy intercept relay (activated by PCDU at the end of the coast phase); arming relays (activated by the arming timer hardware); selection relays (activated by Command and Data Management Unit, CDMU, software). In addition, safe/arm plugs are provided on the unit itself for ground operations.

5.2 Operational modes

Cruise phase The EPSS is completely OFF over the whole cruise phase, except for periodic checkout operations. There is no power at the Orbiter interface and direct monitoring by the Orbiter allows verification that all the relays are open.

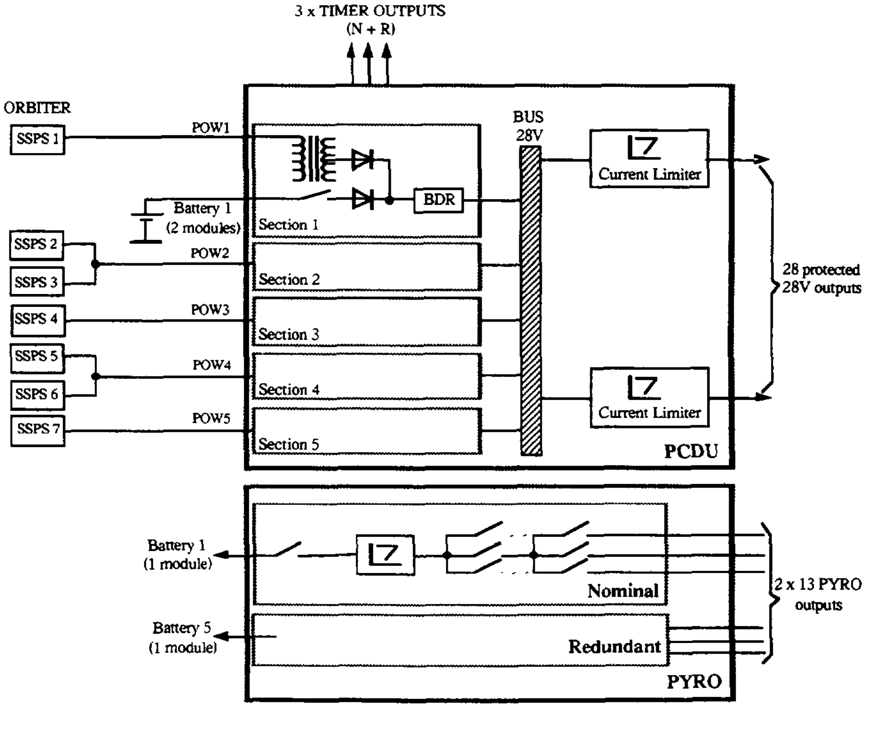


Fig. 10. Huygens Probe Electrical Power Subsystem (EPSS). The power lines (POWs) from the Orbiter to BDR's sections are called: SSPS 1 to BDR 1 = POW1; SSPS 2 + SSPS 3 to BDR 2 = POW2; SSPS 4 to BDR 3 = POW3; SSPS 5 + SSPS 6 to BDR 4 = POW4; SSPS 7 to BDR 5 = POW5. BDR: Battery Discharge Regulator; POW: power line; SSPS: Solid State Power Switch.

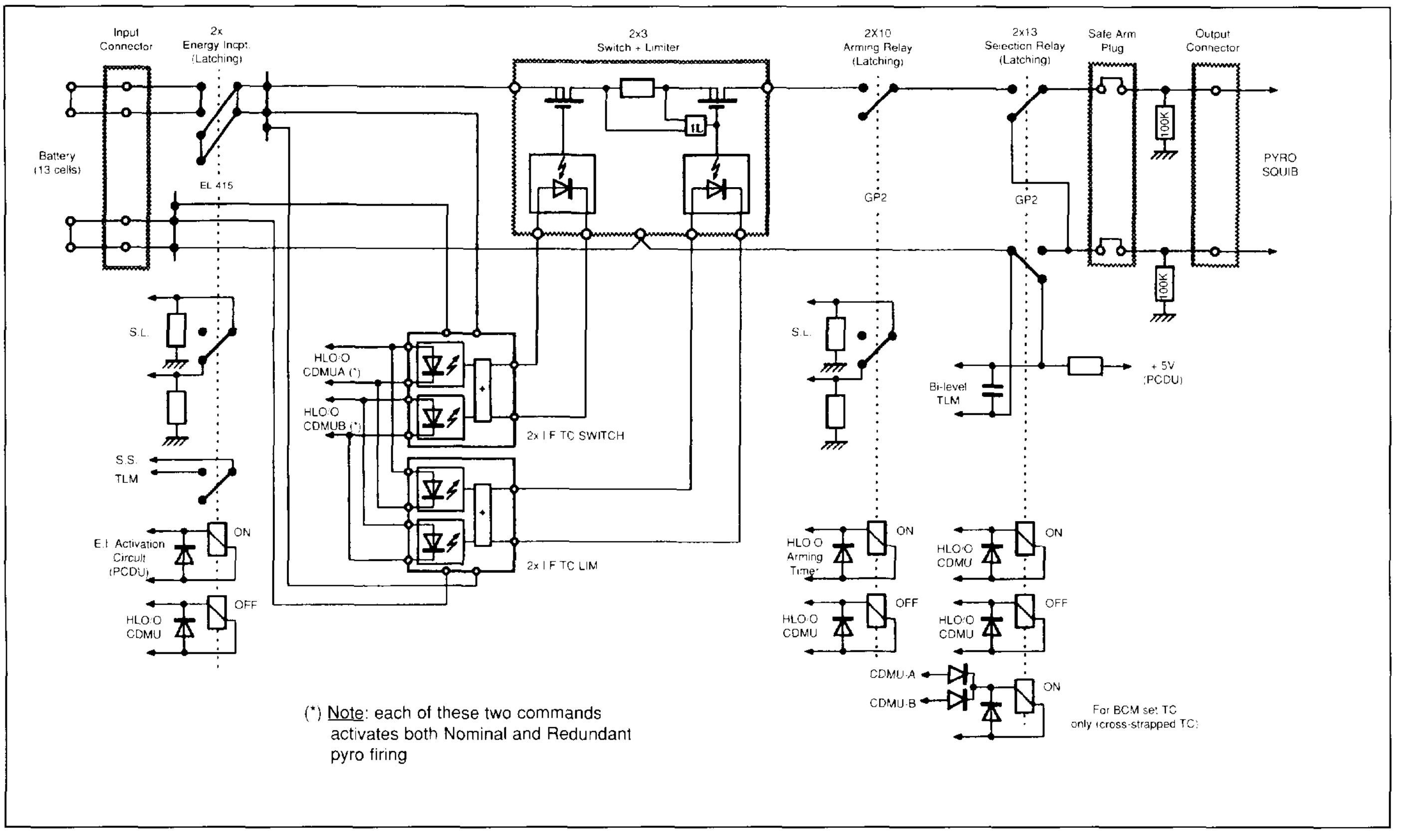


Fig. 11. Configuration of the Huygens Probe pyro unit. BCM: Back Cover Mechanism; CDMU: Command and Data Management Unit; HLO/O: High Level On/Off; I/F: intermediate frequency; PCDU: Power Conditioning & Distribution Unit; SL: Switch & Limiter; SS: Subsystem; TC: telecommand; TLM: telemetry.

Cruise phase checkout The EPSS is powered by the Orbiter for cruise checkout operations. The 28 V bus is regulated by the EPSS BDRs associated with each Orbiter SSPS; a total of 210 W is available from the Orbiter and all the relays are open.

Timer loading Following the loading (from the Orbiter) of the correct coast time duration into the Mission Timer Unit, battery depassivation is performed to overcome any energy loss due to ageing during cruise. Before Probe separation, the EPSS timer relays are closed to supply the Mission Timer from the batteries and the Orbiter power is switched off.

Coast phase Only the Mission Timer is supplied by batteries through specific timer relays during the coast phase. The EPSS is OFF and all other relays are open.

End of coast phase — Probe wake-up At the end of the coast phase, the Mission Timer wakes the Probe by activating the EPSS. Input relays are closed and the current limiters powering the CDMU are automatically switched ON as soon as the 28 V bus reaches its nominal value (other current limiters are initially OFF at power up). The pyro energy intercept relay is also automatically switched on by a command from the PCDU.

Entry and descent phases All PCDU relays are closed and the total power (nominal 300 W, maximum 400 W) is available on the 28 V distribution outputs to subsystems and equipment. The Pyro Unit performs the selection and the firing of the squibs, activated by CDMU commands.

6. Command & Data Management Subsystems (CDMS)

The data handling and processing functions are divided between the Probe Support Equipment (PSE) on the Orbiter and the CDMUs (part of the CDMS) in the Probe (Fig. 12). The Probe Data Relay Subsystem (PDRS) provides the RF link function for this purpose, together with the data handling and communication function with the Orbiter's Control and Data Subsystem (CDS) via a Bus Interface Unit (BIU). (During the ground operations and cruise phase checkouts, the Orbiter-Probe RF link is replaced by umbilical connections.)

The CDMS has two primary functions: autonomous control of Probe operations after separation; management of data transfer from the equipment, subsystems and experiments to the Probe transmitter for relay to the Orbiter. For these functions, the CDMS uses the Probe On-board Software (POSW), for which it provides the necessary processing, storage and interface capabilities.

The driving requirement of the CDMS design is intrinsic single point failure-tolerance. As a result of the highly specific Huygens mission (limited duration and no access by telecommand after separation), a very safe redundancy scheme has been selected. As shown in Fig. 12, the CDMS therefore comprises:

— two identical CDMUs
— a triply redundant Mission Timer Unit (MTU)
— two mechanical *g*-switches (backing up MTU)
— a triply redundant Central Acceleration Sensor Unit (CASU)
— two sets of two mechanical *g*-switches (backing up CASU)
— a Radial Acceleration Sensor Unit (RASU) with two accelerometers
— two Radar Altimeter proximity sensors, each comprising separate electronics, transmit antenna and receive antenna

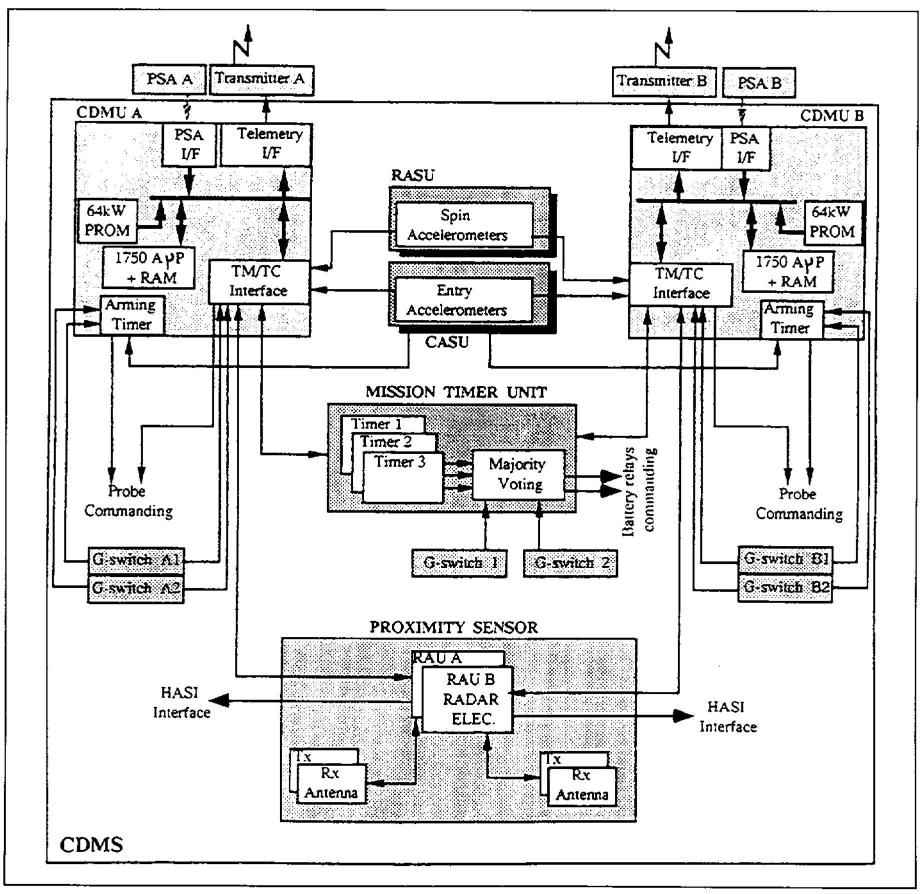


Fig. 12. The Probe's Command and Data Management Subsystems (CDMSs). CASU: Central Acceleration Sensor Unit; CDMU: Command and Data Management Unit; HASI: Huygens Atmospheric Structure Instrument; I/F: intermediate frequency; PSA: Probe Support Avionics; RASU: Radial Acceleration Sensor Unit; TC: telecommand; TM: telemetry.

The two CDMUs each execute their own POSW simultaneously and are configured with hot redundancy (Chain A and Chain B). Each hardware chain can run the mission independently. They are identical in almost all respects; the following minor differences facilitate simultaneous operations and capitalise on the redundancy:

- telemetry is transmitted at two different RF frequencies
- chain B telemetry is delayed by about 6 s to avoid loss of data should a temporary loss of the telemetry link occur (e.g. from an antenna misalignment as the Probe oscillates beneath the parachute).

Each CDMU chain incorporates a health check (called the Processor Valid status) which is reported to the experiments in the Descent Data Broadcasts (DDBs). A chain declares itself invalid when two bit errors in the same memory word, an ADA exception or an under-voltage on the 5 V line occur within the CDMU.

6.1 Command and Data Management Unit (CDMU)

Each CDMU includes a MAS 281 16-bit 1750A micro-processor running at 10 MHz, with 64 kword PROM storing the POSW and 64 kword RAM used for the POSW and other dynamic data when the CDMU is on. A Memory Management Unit is implemented to provide memory flexibility and some growth potential. Direct Memory Access (DMA) is provided to facilitate data transfer between the memory and the input/output registers, thus relieving the microprocessor of repetitive input/output tasks. The RAM-stored program memory is protected against single error occurrence by an Error Detection And Correction (EDAC) device, which detects and corrects single bit errors and reports any double bit errors to the Processor Valid function.

TM/TC management is based on an internal On-Board Data Handling (OBDH) bus in order to standardise the internal interfaces, which are based on the classical Central Terminal Unit (CTU) and Remote Terminal Units (RTUs) approach.

In addition to conventional CDMS functions, the CDMUs implement the following Huygens-specific functions:

- the arming timer function sends pyro and arming commands following a specific hardware-managed timeline, thus offering full decoupling from the POSW operation
- the Processor Valid signal is sent to experiments via the Descent Data Broadcast (DDB), indicating the health of the nominal CDMU (unit A)
- reprogrammability through the use of 16 kword of Electrically Erasable PROM (EEPROM), thus allowing patching of the POSW if necessary
- the EDAC error count reports on internal data transfers
- the capability, through specific 16 kword of RAM, to delay one telemetry chain.

6.2 Mission Timer Unit (MTU)

The MTU is used to activate the Probe at the end of the coast phase. To obtain a single point failure-free design, it is based on three independent hot redundant timer circuits followed by two hot-redundant command circuits. Two mechanical *g*-switches provide backup. MTU power is supplied directly via three 65 V supply lines, one for each Timer Board, from independent batteries.

During the pre-separation programming activities, when the Probe is still connected to the Orbiter, all three Timers are programmed with the exact duration of the coast phase via serial memory load interfaces from one of the two CDMUs. Each of the three Timer Boards can be loaded independently from either CDMU. The programmed values can be verified by the serial telemetry channels. When programming is finished, the CDMUs and all other Probe systems except the MTU are turned off and the Probe is separated.

During the coast phase of about 22 days, the programmed Timer register is decremented by a very precise clock signal. The MTU consumes about 300 mW during this period as only the necessary circuits (CMOS-based) are powered. When the Command Board majority voting detects either both *g*-switches active or at least two of the three 'time-out' signals received, five High Level Commands (HLCs) are issued sequentially from each Board to the PCDU in order to switch on both CDMUs. The timer then returns to a standby mode.

The two *g*-switches, which ensure Probe wake-up in the event of atmospheric entry without the time-out signal from any of the Timer boards, are purely mechanical devices closed when deceleration reaches 5.5-6.5 *g*.

6.3 Central Acceleration Sensor Unit (CASU)

The CASU measures axial deceleration at the centre of the Experiment Platform during entry. The signal is processed by the CDMU to calculate the time for parachute deployment (T_0). The CASU operates within 0-10 *g* and uses a scale factor of 0.512 V/*g*. Its main building blocks are:

1. Power circuit. Two hot-redundant input power lines make it single point failure-tolerant in both nominal and redundant power lines
2. Three accelerometer analogue signal conditioning blocks. A low-pass filter with a 2 Hz cutoff is used and the analogue output from each block is routed to both CDMUs. In addition, the design prevents failure propagation from one conditioning chain to the others, it withstands permanent short circuit conditions without any degradation, and it is single point failure-tolerant toward the input power supply line.

Back-up detection of T_0 is performed separately for both CDMUs by two pairs of mechanical *g*-switches in case the prime CASU system is inoperative. The threshold values for each pair of *g*-switches are 5.5 *g* and 1.2 *g*.

6.4 Radial Acceleration Sensor Unit (RASU)

The RASU measures radial acceleration at the periphery of the Experiment Platform. The signal is processed by the CDMU to provide the Probe spin rate for insertion into the DDB distributed to experiments. The RASU is designed to measure spin acceleration within 0-120 m*g* with a 41.67 V/*g* scale factor. The design is based on CASU's but includes only two accelerometers.

6.5 Radar Altimeter Unit (RAU)

The RAU proximity sensor uses two totally redundant altimeters operating with frequency-modulated carrier waves at 15.4 GHz and 15.8 GHz to measure altitude above Titan's surface, starting from about 25 km. Each of the four antennas (two per altimeter) is a planar slot radiator array providing an antenna gain of 25 dB with a symmetrical full beam width of 7.9°. A continuous signal modulated in frequency with a rising and falling ramp waveform is transmitted; the received signal has a similar form, but delayed by the propagation time. Hence the range to target is proportional (with a linear frequency modulation ramp) to the instantaneous frequency shift between the transmitted and received signals. Received signal data are also provided to the Huygens Atmospheric Structure Instrument (HASI) to establish Titan's surface roughness and topography.

7. Probe Data Relay Subsystem (PDRS)

The PDRS (Fig. 13) is Huygens' telecommunications subsystem, combining the functions of RF link, data handling and communications with the Orbiter. It transmits science and housekeeping data from the Probe to the Orbiter's PSE, which are then relayed to the Orbiter CDS via a Bus Interface Unit. In addition, the PDRS is responsible for TC distribution from the Orbiter to the Probe by umbilical during the ground and cruise checkouts. It comprises:

1. two hot-redundant S-band transmitters and two circularly polarised Probe Transmitting Antennas (PTAs) on the Probe
2. a Receiver Front End (RFE) unit (enclosing two Low Noise Amplifiers and a diplexer) and two Probe Support Avionics (PSA) units on the Orbiter.

The Orbiter's High Gain Antenna (HGA) acts as the PDRS receive antenna.

In addition, as part of the Doppler Wind Experiment (DWE), two ultra stable oscillators are available as reference signal sources to allow the accurate measurement of the Doppler shift in the Probe-Orbiter RF link: the Transmitter Ultra Stable Oscillator (TUSO) on Huygens and the Receiver Ultra Stable Oscillator (RUSO) on the Orbiter.

The PDRS electrical architecture is fully channelised for redundancy, except that TUSO and RUSO are connected to only one chain.

7.1 Probe Support Equipment (PSE)

7.1.1 Receiver Front End (RFE)

The RFE comprises:

- two Low Noise Amplifiers (LNAs) linked to the Orbiter's HGA to amplify the acquired RF signal by 20 dB using two cascaded FET stages
- two RF inputs: one linked to the HGA, the other via a coupler and used during checkout to link a dedicated transmitter output (on the Probe) to the RFE via the umbilical
- a pre-selection filter (coaxial cavity type with six poles)
- an isolator
- an output attenuator (fixed value)

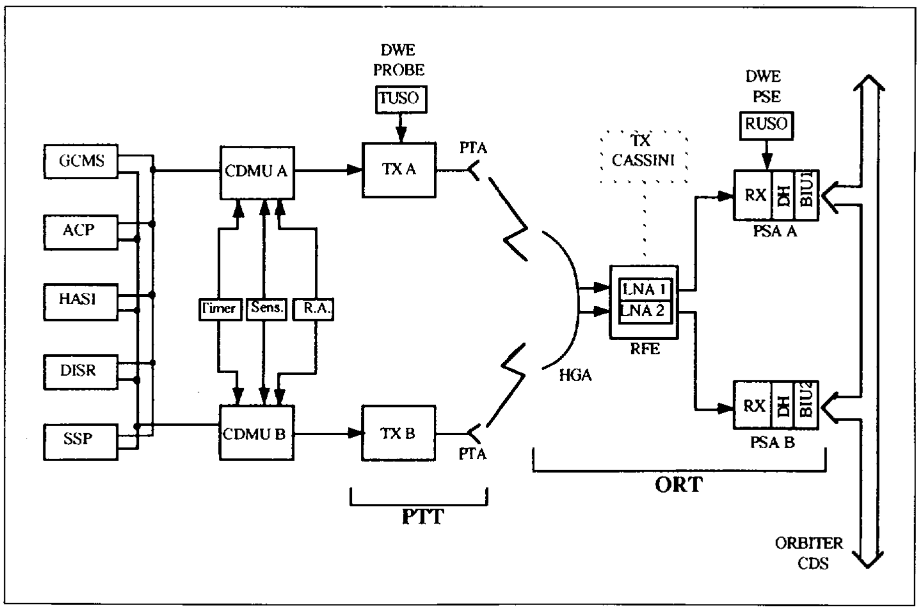


Fig. 13. The Probe Data Relay Subsystem (PDRS). ACP: Aerosol Collector and Pyrolyser; CDMU: Command and Data Management Unit; DISR: Descent Imager/Spectral Radiometer; DWE: Doppler Wind Experiment; GCMS: Gas Chromatograph Mass Spectrometer; HASI: Huygens Atmospheric Structure Instrument; LNA: low noise amplifier; ORT: Orbiter Receiving Terminal; PTA: Probe Transmitting Antenna; PTT: Probe Transmitting Terminal; RA: Radar Altimeter; SSP: Surface Science Package.

In addition, owing to the HGA's shared use with the Orbiter, a band pass filter (the Tx filter) and a circulator protect the LNA chain B by isolating the Orbiter's S-band transmissions and the Probe's S-band reception, which both use the HGA. These two modes are mutually exclusive.

7.1.2 Probe Support Avionics (PSA)

The two RFE outputs are sent to the two PSAs, which perform detection, acquisition (based on a 256-point Fast Fourier Transform algorithm), tracking, signal demodulation and data handling & management. The PSA data handling architecture is divided between analogue and digital sections. The analogue section performs signal down-conversion from S-band to the IF frequency. The IF signal is quantised and the samples processed by the digital section. The digital section performs:

- the Digital Signal Processing (DSP) function — the signal acquisition and tracking task based on FFT analysis and frequency acquisition
- the Viterbi decoding of the digital signal and delivery of the decoded transfer frame to the data handling section at 8192 bit/s
- the data handling task, which consists of:
  - transforming the received transfer frame into a telemetry packet
  - generating internal PSA housekeeping data (including the synthesised frequency information) in a packet format
  - controlling and managing communications with the Orbiter CDS via a Bus Interface Unit
  - distributing the telecommands from the Orbiter BIU interface.

The digital section is composed of the following main modules:

- the receiver digital module, comprising the UT1750 microprocessor, 8 kword RAM and 8 kword PROM, and the receiver signal processing ASIC
- the interface digital module, using GaAs devices for Numerically Controlled Oscillator (NCO) and Digital to Analogue Converter (DAC) functions
- the support interface circuitry module (SIC), which comprises: the 8 kword EEPROM to memorise software patches; the 32 kword PROM containing the Support Avionics Software (SASW) and the testing, telecommand, telemetry and umbilical interfaces; the MAS 281 microprocessor module used by the SASW
- the BIU module that controls communications between the PSA and the Orbiter's 1553 bus.

7.2 Probe Transmitting Terminal (PTT)

The PTT comprises two transmitters and two Probe antennas. Each transmitter includes Temperature Controlled Crystal Oscillator (TCXO) synthesiser and BPSK modulator modules and a 10 W Power Amplifier module using Automatic Level Control (ALC) for 40.2 dBm nominal output power (end-of-life, worst-case, including ageing).

The reference oscillator for the Phase Locked Loop (PLL) synthesiser is either an (internal) Voltage Controlled Crystal Oscillator (VCXO) with a temperature compensating network or the (external) TUSO signal. The selection between these reference sources is made before separation from the Orbiter. The TUSO has priority unless a failure is detected before separation.

The two transmitting antennas linked to the transmitters (dual chains without cross-coupling) are quadrifilar helix designs. The four spirals are fed at the bottom of the helix in phase quadrature. Left Hand Circular Polarisation (LHCP) is used for signal transmission at 2040 MHz and Right Hand Circular Polarisation (RHCP) for transmission at 2098 MHz. The minimum gain for the antennas, mounted on the Top Platform, is 0.9 dB at all Probe-Orbiter aspect angles between +20° and +60°.

7.3 Probe data relay link budget

During Probe descent, starting from the time of atmospheric entry as predicted from Orbiter trajectory and Probe separation characteristics, the Orbiter HGA is controlled to track a fixed point on Titan's surface — the nominal touchdown point. Orbiter movement along its trajectory significantly reduces the 'space loss' due to link distance during the Probe's 2-2.5 h descent. However, if Huygens does not land at the nominal point, e.g. due to non-nominal entry parameters or zonal winds, the gain from the reduced distance is offset by the HGA's reduced gain from the off-axis angle of the Probe with respect to the HGA's boresight axis. This can be seen by comparing the Beginning of Mission (BOM) and End of Mission (EOM) values in Table 4.

The link budget worst cases occur at the beginning and end of mission. The link design attempts to equalise the BOM/EOM signal level margins. At BOM, the signal level is determined by the range, while the losses owing to off-axis pointing is mainly due to HGA pointing error and Probe delivery error (the additional dispersion arising from the entry phase is relatively minor). At EOM, however, the signal level is

Table 3. Probe data relay (nominal) link budget, Beginning of Mission (BOM) and End of Mission (EOM). T_0 marks the beginning of the parachute deployment sequence.

		BOM (T_0+2.5 min)	EOM (nominal landing + 3 min)
Probe			
Transmittal power	dBm	40.66	40.66
Antenna (equivalent) gain	dB	1.04	1.04
EIRP (equivalent isotropic radiated power)	dBm	41.7	41.7
Free space loss	dB	−196.367	−186.381
Titan atmospheric loss	dB	−0.050	−0.050
Orbiter			
High Gain Antenna peak gain	dBi	34.7	34.7
Off-axis (pointing) loss	dB	−0.549	−9.500
Polar/coupling/filter losses	dB	−0.460	−0.460
Noise density at Low Noise Amplifier	dBm/Hz	−174.985	−174.985
At Probe Support Equipment (PSE) input			
Received signal power	dBm	−120.917	−119.831
Carrier/Noise ratio (C/No)	dBHz	54.069	55.154
Probe Support Equipment			
Data degradation losses	dB	−4.451	−4.451
Threshold C/No for acquisition	dBHz	41.000	41.000
Margin on carrier recovery	dB	**8.618**	**9.703**
Data modulation losses	dB	−2.497	−2.497
Data power to receiver	dBm	−123.413	−122.328
Signal/Noise (Eb/No) to receiver	dB	12.438	13.524
Distortion losses	dB	−2.300	−2.300
Eb/No	dB	10.138	11.224
Threshold Eb/No for data	dB	2.55	2.55
Margin on data recovery	dB	**7.588**	**8.674**

Table 4. Probe data relay link budget margins BOM/EOM.

		2040 MHz		*2098 MHz*	
Margin (dB)		*Nominal*	*Adverse*	*Nominal*	*Worst-case*
Margin on carrier acquisition	BOM	8.618	7.194	8.403	7.363
	EOM	9.703	7.370	7.606	5.816
Margin on data recovery	BOM	7.588	6.638	7.705	6.910
	EOM	8.674	7.174	6.908	5.363

critically dependent on the descent duration: the off-axis pointing losses due to the Probe's lateral drift in the assumed Titan wind worsens with descent duration. The effect of these adverse effects on the two Probe RF links compared to the nominal case is given in Table 4.

8. Software

8.1 Concept

The Huygens software consists of that running in the Probe CDMS, referred to as POSW, and that within the PSA on the Orbiter, referred to as the Support Avionics Software (SASW). The POSW output telemetry is relayed via the SASW and then Cassini's CDS to the ground. Two copies of the data handling hardware (CDMU and PSA) run identical copies of POSW and SASW.

The software is based on a top-down hierarchical and modular approach using the Hierarchical Object-Oriented Design (HOOD) method and, except for some specific low level modules, is coded in ADA. The software consists, as much as possible, of a collation for synchronous processes timed by a hardware reference clock (8 Hz repetition rate). In order to avoid unpredictable behaviour, interrupt-driven activities are minimised. Such a design also allows a better observability and reliability of the software. Limited reprogramming accommodates modifications and RAM failure recoveries.

The processes are designed to use data tables as much as possible. Mission profile reconfiguration and experiment polling can therefore be changed only by reprogramming these tables. This is possible via an EEPROM. In order to avoid a RAM modification while the software is running (which can lead to unpredictable behaviour and unnecessary complexity), direct RAM patching is forbidden.

The POSW communicates with the SASW in different ways depending on mission phase. Before Probe separation, the two software subsystems communicate via an umbilical that provides both command and telemetry interfaces. Huygens cannot be commanded after separation, and telemetry is transmitted to the Orbiter via the PDRS RF link.

The overall operational philosophy is that the software runs the nominal mission from power-up without checking its hardware environment or the Probe's connection or disconnection. The specific software actions or inhibitions required for ground or flight check-out must therefore be invoked by special procedures, activated by the delivery of specific telecommands to the software.

To achieve this autonomy, POSW's inflight modification is autonomously applied at power-up by using a non-volatile EEPROM. At power-up, the POSW validates the CDMU EEPROM structure and then applies any software patches stored in the EEPROM before running the mission mode. If the EEPROM proves to be invalid at start-up, no patches are applied and the software continues based on the software in the CDMU ROM. A number of other checks are also carried out at start-up (e.g. a DMA check and a main ROM checksum), but the software will continue execution attempts even if the start-up checks fail.

8.2 POSW functions

The POSW provides the following functions:

Probe Mission Management

- detecting time T_0 as entry begins, based on the Central Accelerometer Sensor Unit signals
- forwarding commands at the correct times to the subsystems and experiments according to the pre-defined mission timeline

— computation of the spacecraft dynamical state from sensor readings
— sending Descent Data Broadcasts to the experiments

Telemetry Management
— collecting and recording housekeeping data
— generation of housekeeping packets from the housekeeping data
— collecting experiment packets according to a pre-defined polling scheme
— transmitting transfer frames to the PDRS

Telecommand Management
— reception of TC packets from the PSE (only while attached to the Orbiter)
— execution of commands related to these TC packets
— forwarding of commands to the experiments

8.3 POSW operations

Control of the Probe, involving the activation and forwarding of commands to experiments and subsystems, is driven by a pre-defined set of tables, the Mission Timeline Tables (MTTs), that define the actions to be performed as a function of time. The pre-T_0 MTT is activated at Probe wake-up, and controls the Probe until the post-T_0 MTT is activated by the POSW's detection of T_0.

The experiments perform most of their activities autonomously based on the mission phase data computed within the POSW and sent to all the experiments every 2 s as a Data Descent Broadcast packet. The DDB contains the time, spin rate (computed by the POSW from the RASU signal or, in the event of failure, from a pre-defined look-up table) and altitude (initially taken from a look-up table based on the time elapsed since T_0, but later by processing RAU data).

The telemetry management function involves the acquisition and transmission of Probe telemetry as standard packets (ESA PSS-04 106). Whether they are housekeeping or experiment packets, they are all 126 bytes long and forwarded to the SASW in the form of transfer frames comprising header information followed by seven packets and then Reed-Solomon code words, making a total frame size of 1024 bytes.

Housekeeping data are acquired from the subsystems (and from the software itself) at different rates according to a pre-determined packet layout, and are loaded into four packets every 16 s. One of the packet types is buffered and issued 6.4 min later as 'History' housekeeping.

Experiment data are acquired according to a pre-defined polling strategy and the resulting packets are loaded into the transfer frames. The selection of an appropriate type of telemetry packet to include in each of the frame's seven slots is managed by the polling sequence mechanism on a major acquisition cycle of 16 s (equal to 128 Computer Unit Times) driven by the Polling Sequence Table (PST) and the Experiment Polling Table (EPT). The PST defines if housekeeping or experiment packets are to be included in the transfer frame currently under construction. However, it does not select which experiment is to be included. The EPT defines a prioritised scheme for the collection of experiment data. The table is invoked whenever the PST requests experiment data for the transfer frame and is read in a cyclical manner. It consists of a sequential list of the Huygens experiments, with the number of occurrences of each experiment in the table providing the polling priority.

By this method, the CDMS and the POSW are protected against failure modes in the experiments that could affect the data production rates. Each experiment is guaranteed an opportunity to supply data at, as a minimum, its nominal data rate. Furthermore, this polling scheme automatically optimises the data return by reallocating the TM resource in the absence of a 'packet ready' status flag from an experiment when expected.

Three EPTs provide different polling priorities during the descent's various stages, switching from one table to the next at a pre-set time.

8.4 SASW functions

The SASW's main purpose is to provide communications between the Orbiter and Probe. For the SASW, there is no difference between receiving Probe telemetry via the umbilical or via the RF subsystem. All the differences are handled by the PDRS receiver part of the PSA equipment. The SASW provides the following functions:

Telecommand Management

- reception of TC packets from the BIU interfacing with the Orbiter CDS
- execution of commands related to these TC packets
- forwarding TC packets to the CDMS (including experiment telecommands) while attached to the Orbiter

Telemetry Management

- collecting PSE housekeeping data
- transmitting PSE housekeeping packets and modified CDMS frames to the Orbiter via the BIU

8.5 SASW operations

Communication between the SASW and the Orbiter CDS is via a MIL-STD-1553 bus using a BIU. Received telecommands are placed in BIU memory for the SASW to read; the SASW places telemetry packets in BIU memory for transmission by the BIU over the CDS bus. The SASW examines any received telecommands to determine their destination address. Those destined for the Probe (subsystems or experiments) are transmitted over the umbilical TC link. Those for the PSA are handled by the SASW.

The SASW handles the reception of Probe telemetry via a Frame Data Interface (FDI). Telemetry from the Probe is transmitted to the SASW either by the umbilical RF link when the probe is connected or by the Probe Relay Link (PRL) after separation. The SASW also generates its own telemetry in the form of housekeeping packets, containing PSA status information, and status data collected from the PDRS subsystem.