Chapter 10. Telecommunications

Objectives: Upon completion of this chapter you will be aware of the major factors involved in communicating across interplanetary distances. You will also be aware that detailed coverage of this subject appears in a separate course.

This chapter gives a broad view of some telecommunications issues, including both spacecraft and Earth-based communication. This view is of abbreviated depth, and the subject is covered further by a separate Space Flight Operations Multi-team Training Module for employees at JPL, "End-to-end Information System" (refer to the illustration in the Introduction on page 1). Details of onboard spacecraft equipment for telecommunications are covered under Telecommunications Subsystems in Chapter 11.

Signal Power

Your local entertainment radio broadcast station may have a radiating power of 50 kW, and the transmitter is probably no more than 100 km away. Your portable receiver probably has a simple antenna inside its case. Spacecraft have nowhere near that amount of power available for transmitting, yet they must bridge distances measured in tens of billions of kilometers. A spacecraft might have a transmitter with no more than 20 watts of radiating power. How can that be enough? One part of the solution is to employ microwave frequencies, concentrate all available power into a narrow beam, and then to send it in one direction instead of broadcasting in all directions. This is typically done using a parabolic dish antenna on the order of 1 or 5 meters in diameter. Even when these concentrated signals reach Earth, they have vanishingly small power. The rest of the solution is provided by the DSN's large aperture reflectors, cryogenically-cooled low-noise amplifiers and sophisticated receivers, as well as data coding and error-correction schemes.

Uplink and Downlink

The radio signal transmitted to a spacecraft is known as uplink. The transmission from spacecraft to Earth is downlink. Uplink or downlink may consist of a pure RF tone, called a carrier, or carriers may be modulated to carry information in each direction. Commands transmitted to a spacecraft are sometimes referred to as an upload. Communications with a spacecraft involving only a downlink are called one-way. When an uplink is being received by the spacecraft at the same time a downlink is being received at Earth, the communications mode is called "two-way."

Modulation and Demodulation

Consider the carrier as a pure tone of, say, 3 GHz, for example. If you were to quickly turn this tone off and on at the rate of a thousand times a second, we could say it is being modulated with a frequency of 1 kHz. Spacecraft carrier signals are modulated, not by turning off and on, but by shifting each waveform's phase slightly at a given rate. One scheme is to modulate the carrier with a frequency, for example, near 1 MHz. This 1 MHz modulation is called a subcarrier. The subcarrier is in turn modulated to carry individual phase shifts that are designated to represent groups of binary 1s and 0s—the spacecraft's telemetry data. The amount of phase shift used in modulating data onto the subcarrier is referred to as the modulation index, and is measured in degrees. The same kind of scheme is also used on the uplink.

Demodulation is the process of detecting the subcarrier and processing it separately from the carrier, detecting the individual binary phase shifts, and decoding them into digital data for further processing. The same processes of modulation and demodulation are used commonly with Earth-based computer systems and fax machines transmitting data back and forth over a telephone line. The device used for this is called a modem, short for modulator / demodulator. Modems use a familiar audio frequency carrier which the telephone system can readily handle.

Binary digital data modulated onto the uplink is called command data. It is received by the spacecraft and either acted upon immediately or stored for future use or execution. Data modulated onto the downlink is called telemetry, and includes science data from the spacecraft's instruments and spacecraft health data from sensors within the various onboard subsystems.

Multiplexing

Not every instrument and sensor aboard a spacecraft can transmit its data at the same time, so the data are multiplexed. In the time-division multiplexing (TDM) scheme, the spacecraft's computer samples one measurement at a time and transmits it. On Earth, the samples are demultiplexed, that is, assigned back to the measurements that they represent. In order to maintain synchronization between multiplexing and demultiplexing (also called mux and demux) the spacecraft introduces a known binary number many digits long, called the pseudo-noise (PN) code at the beginning of every round of sampling (telemetry frame), which can be searched for by the ground data system. Once recognized, it is used as a starting point, and the measurements can be demuxed since the order of muxing is known.

Newer spacecraft use packetizing rather than TDM. In the packetizing scheme, a burst or packet of data is transmitted from one instrument or sensor, followed by a packet from another, and so on, in non-specific order. Each burst carries an identification of the measurement it represents for the ground data system to recognize it and handle it properly. These schemes generally adhere to the International Standards Organization (ISO)'s Open Systems Interconnection (OSI) protocol suite, which recommends how computers of various makes and models can inter communicate. The ISO OSI is distance independent, and holds for spacecraft light-hours away as well as between workstations.

Coherence

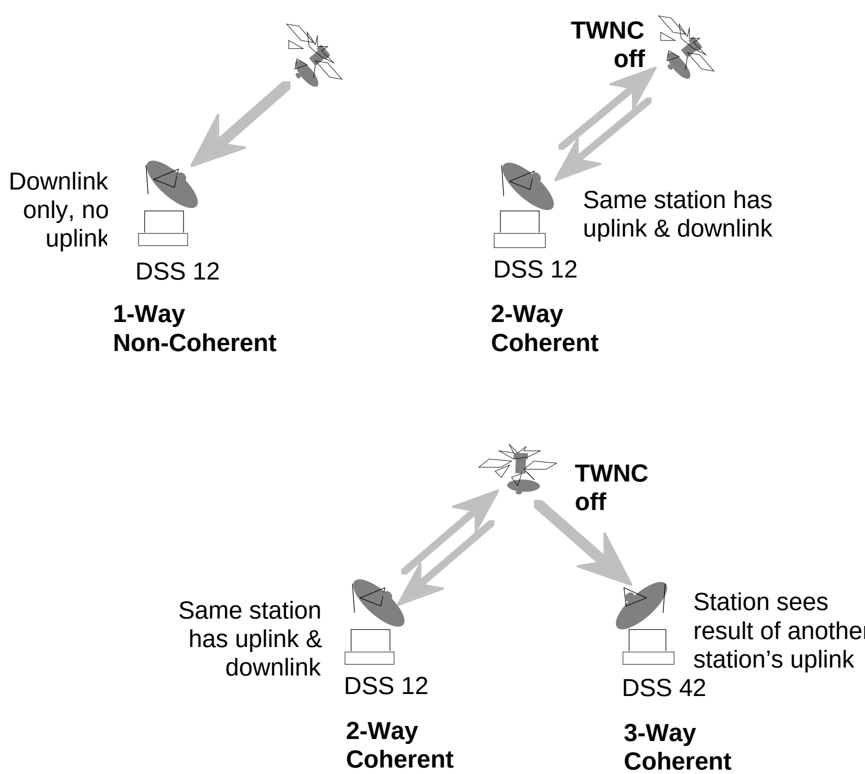
Aside from the information modulated on the downlink as telemetry, the carrier itself is used for tracking the spacecraft, and for carrying out some types of science experiments. For each of these uses, an extremely stable downlink frequency is required, so that Doppler shifts on the order of fractions of a Hertz may be detected out of many GHz over periods of hours. But it would be impossible for any spacecraft to carry the massive equipment on board required to generate and maintain such stability. The solution is to have the spacecraft generate a downlink which is phase coherent to the uplink it receives.

Down in the basement of each DSN Signal Processing Center, there looms a hydrogen-maser based frequency standard in an environmentally controlled room. This is used as a reference for generating an extremely stable uplink frequency for the spacecraft to use in generating its coherent downlink.

The resulting spacecraft downlink, based on and coherent with an uplink, has the same extraordinarily high frequency stability as does the massive hydrogen maser-based system in its controlled environment in the DSN basements. It can thus be used for precisely tracking the spacecraft, and for carrying out science experiments. The spacecraft also carries a low mass oscillator to use as a reference in generating its downlink for periods when an uplink is not available, but it is not highly stable, and its output frequency is affected by temperature variations on the spacecraft. Some spacecraft carry an Ultra-Stable Oscillator (USO), discussed further in Chapter 16. Because of the stringent frequency requirements for spacecraft operations, JPL stays at the forefront of frequency and timing standards technology.

Most spacecraft may also invoke a non-coherent mode which does not use the uplink frequency as a downlink reference. Instead, the spacecraft uses its onboard oscillator as a reference for generating its downlink frequency. This mode is known as Two-Way Non-Coherent (TWNC, pronounced "twink"). When TWNC is on, the downlink is non-coherent.

Recall that "two-way" means there is an uplink and there is a downlink, and doesn't indicate whether the spacecraft's downlink is coherent to that station's uplink or not. However, in common usage, operations people commonly say "two-way" to mean "coherent," which is generally the case. Correctly stated, a spacecraft's downlink is coherent when it is two-way with TWNC off. When a spacecraft is receiving an uplink from one station and its coherent downlink is being received by another station, the downlink is said to be "three-way" coherent.



Recap

1. The subject of telecommunications is covered further by a separate Space Flight Operations Multi-team Training Module for employees at JPL, " _________ - ____ - ________ __________________ ______________ ."
2. When an uplink is being received by the spacecraft at the same time a downlink is being received at Earth, the communications mode is called __________ - ___________.
3. Spacecraft carrier signals are modulated, not by turning off and on; but by shifting each waveform's ____________ slightly at a given rate.
4. A spacecraft downlink, based on and coherent with an uplink, has the same extraordinarily high ___________________ stability as does the massive hydrogen maser-based system in its controlled environment.
5. A spacecraft's downlink is ______________ when it is two-way with TWNC off.

1. End-to-end Information System   2. two-way   3. phase   4. frequency   5. coherent

Chapter 11. Typical Onboard Subsystems

Objectives: Upon completion of this chapter you will be able to describe a typical spacecraft structural subsystem, the role of data handling subsystems, attitude and articulation control subsystems, telecommunications subsystems, electrical power and distribution subsystems, and propulsion subsystems on typical spacecraft. You will be able to list advanced technologies being considered for use on future spacecraft.

Subsystems and Systems

Individual spacecraft can be very different from one another, and they display many different approaches to solving similar problems. Some newer spacecraft are designed to be smaller and less massive than some of their predecessors. Yet there are common functions that are carried out by many deep-space traveling robots, no matter how massive or miniature the spacecraft. Not all classifications of spacecraft have the same subsystems, though. Atmospheric balloon packages, for example, are simple packages compared to a typical orbiter. The following discussions address a number of different subsystems that satisfy the requirements typical of orbiter or flyby class spacecraft. Subsystems typical of the ones described below become integrated into a total space flight system, the spacecraft.

Structural Subsystems

The spacecraft bus is a major part of the structural subsystem which provides a place to attach components internally and externally, and to house delicate modules requiring the protection of an environment with a measure of thermal and mechanical stability. It is an integral card chassis for supporting the circuit boards of radio equipment, data recorders, computers, gyroscopes, and other components. The bus also establishes the basic geometry of the spacecraft, and it provides the attachment points for appendages such as booms, antennas, and scan platforms. It also provides attachment points that allow movement of the spacecraft during construction, testing, transportation, and launch.

The magnetometer boom is typically the longest appendage on a spacecraft. Since magnetometers (discussed in Chapter 12) are sensitive to electric currents and ferrous components on or near the spacecraft bus, they are placed at the greatest practical distance from them on a boom. The Voyager magnetometers are mounted 6 and 13 meters out the boom from the spacecraft bus. At launch, the mag boom, constructed of thin, non-metallic rods, is typically collapsed very compactly into a protective canister. Once deployed in flight, it cannot be retracted.

Data Handling Subsystems

The onboard computer responsible for overall management of a spacecraft’s activity is generally the same one which maintains timing, interprets commands from Earth, collects, processes, and formats the telemetry data which is to be returned to Earth, and manages high-level fault protection and safing routines. This computer is sometimes referred to as the command and data subsystem (CDS). For convenience, that term will be used here, recognizing that other names may apply to similar subsystems or sets of subsystems which accomplish some or all of the same tasks. Some examples are: Command and Data Handling subsystem (C&DH), Computer Command subsystem (CCS), and Flight Data Subsystem (FDS).

A portion of the CDS memory is managed as storage space for command sequences and programs uplinked from Earth. These sequence loads are typically created by the project's sequence team with inputs from the spacecraft team and the science teams.

Spacecraft Clock

The spacecraft clock (SCLK, pronounced "sklock") is a counter maintained by the CDS. It meters the passing of time during the life of the spacecraft. Nearly all activity within the spacecraft systems is regulated by the SCLK. The spacecraft clock may be very simple, incrementing every second and bumping its value up by one, or it may be more complex, with several main and subordinate fields that can track and control activity at multiple granularities. The Ulysses clock, for instance, increments its single field by one count every two seconds. The Galileo and Magellan clocks, on the other hand, consist of four fields of increasing resolution. Many types of commands uplinked to the spacecraft are set to begin execution at specific SCLK counts. In the downlinked telemetry, SCLK counts indicating telemetry-frame creation time are included with engineering and science data to facilitate processing, distribution, and analysis.

Telemetry Packaging and Coding

The telemetry returned from JPL spacecraft is typically a mixture of science data from the experiments and spacecraft engineering or health data. These data from science instruments and spacecraft subsystems' transducers are received at the CDS, where they are assembled into quanta appropriate to the telemetry frame or packet scheme in use. If the spacecraft is transmitting data in real time, the packet or frame may be sent to the transmitter. Otherwise, telemetry may be written to a mass storage device such as tape recorder or stored in RAM until transmission is feasible.

Spacecraft engineering or health data is composed of a wide range of measurements, from switch positions and subsystem states to voltages, temperatures, and pressures. Literally thousands of these "channels" of data (so named because repetitive measurements are identified with a single multiplexing division or channel) are collected and inserted into the telemetry. A spacecraft may use one or more of a variety of multiplexing schemes to downlink and display all the various measurements.

The capability to alter the telemetry format and content must be provided in order to accommodate various mission phases or downlink rates, as well as to enable diagnosis of anomalies. In the case of anomalies, it may be necessary to temporarily terminate the collection of science data and to return only an enriched or specialized stream of engineering and housekeeping data.

Some data processing may take place within the CDS before science and engineering data are stored or transmitted. Data compression may be applied to reduce the number of bits to be transmitted, and encoding is applied to take advantage of error-correcting schemes that reduce data loss. Viterbi encoding (characterized as "maximum likelihood convolutional coding"), Golay, and Reed-Solomon encoding are commonly used for this purpose. Though some overhead is added to the telemetry stream, the net effect is that more data are transmitted and successfully received error-free per unit time. The data are decoded once captured by the DSN.

Data Storage

It is rare for a mission to be provided the constant support of real-time tracking. For this and other reasons, spacecraft data handling subsystems are provided with one or more data storage devices such as tape recorders, or the solid-state equivalent of tape recorders that store large quantities of data in banks of RAM without any moving parts. The storage devices are commanded to play out their stored data for downlink when DSN resources are available.

Fault Protection

A robotic space flight system must have the intelligence and autonomy to monitor and control itself to a degree throughout its useful life at a great distance from Earth. Though ground teams also monitor and control the spacecraft, the ever-increasing light time limits the ability to respond to conditions on the spacecraft in a timely manner. Fault protection algorithms, which normally reside in more than one of the spacecraft's subsystems, insure the ability both to prevent a mishap and to re establish contact with Earth if a mishap occurs and contact is interrupted. Among the capabilities devised is safing—shutting down or reconfiguring components to prevent damage either from within or from the external environment. Another fault protection capability is an automated, methodical search to re-establish Earth-pointing and regain communications. Usually a minimal set of safing instructions is installed in ROM (1K on Magellan) where it can hide from even the worst imaginable scenarios of runaway computer program execution or power outage. More intricate safing routines (also called "contingency modes") and fault protection routines reside in RAM, as well as parameters for use by the ROM code, where they can be updated as necessary during the life of the mission.

One example of a common fault-protection routine is the Command-Loss Timer. This is a software timer running in CDS which is reset to a predetermined value every time the spacecraft receives a command from Earth. If the timer decrements all the way to zero, the assumption is that the spacecraft has experienced a failure in its receiver or command decoder, or other hardware in the command string. The routine takes actions such as swapping to redundant hardware in an attempt to re establish the ability to receive commands.

Recap

1. Subsystems... become integrated into a total space flight _________________ , the space-craft.
2. The _______________ establishes the basic geometry of the spacecraft, and provides the attachment points for appendages.
3. A portion of the CDS memory is managed as storage space for _________________ _______________ and programs uplinked from Earth.
4. Many types of commands uplinked to the spacecraft are set to begin execution at specific _____________ counts.
5. ________________ encoding (characterized as "maximum likelihood convo-lutional cod-ing"), Golay, and Reed-Solomon encoding are commonly used.
6. _____________ ____________________ algorithms... insure the ability both to prevent a mishap and to re-establish contact with Earth if contact is interrupted.

1. system 2. bus 3. command sequences 4. SCLK 5. Viterbi 6. Fault protection

Attitude and Articulation Control Subsystems

A spacecraft's attitude, its orientation in space, must be stabilized and controlled so that its high-gain antenna may be accurately pointed to Earth, so that onboard experiments may accomplish precise pointing for accurate collection and subsequent interpretation of data, so that the heating and cooling effects of sunlight and shadow may be used intelligently for thermal control, and so that propulsive maneuvers may be executed in the right direction.

Stabilization can be accomplished by setting the vehicle spinning, as do the Pioneers 10 and 11 spacecraft in the outer solar system and the Galileo spacecraft orbiting Jupiter. The gyroscopic action of the rotating spacecraft mass is the stabilizing mechanism. Propulsion system thrusters are fired to make desired changes in the spin-stabilized attitude.

Alternatively, the spacecraft may be designed for active three-axis stabilization. One method is to use small propulsion-system thrusters to nudge the spacecraft back and forth within a deadband of allowed attitude error. Voyagers 1 and 2 have been doing that since 1977. Another method is to use electrically-powered reaction wheels, also called momentum wheels. Massive wheels are mounted in three orthogonal axes aboard the spacecraft. To rotate the vehicle in one direction, you spin up the proper wheel in the opposite direction. To rotate the vehicle back, you slow down the wheel. Excess momentum that builds up in the system due to external torques (caused, for example, by solar photon pressure or gravity gradient), must be occasionally removed from the system via propulsive maneuvers.

There are advantages and disadvantages to either approach. Spin stabilized craft provide a continuous sweeping desirable for fields and particles instruments, but they may require complicated systems to de-spin antennas or optical instruments which must be pointed at targets. Three-axis controlled craft can point optical instruments and antennas without having to de-spin them, but they may have to carry out rotation maneuvers to best utilize their fields and particle instruments.

The attitude and articulation control subsystem (AACS) computer manages the tasks involved in stabilization via its interface equipment. For attitude reference, star trackers, star scanners, solar trackers, sun sensors, and planetary limb trackers come into use. Voyager's AACS uses a sun sensor for yaw and pitch reference, and a star tracker trained continuously on a bright star at right angles to sunpoint for roll reference. Galileo takes its references from a star scanner which rotates with the spinning part of the spacecraft, and a sun gate is available for use in maneuvers. Magellan used a star scanner to take a fix on two bright stars during a special maneuver once every orbit or two, and its solar panels each had a sun sensor.

Gyroscopes are carried for attitude reference for those periods when celestial references are not being used. For some spacecraft, such as Magellan, this is the case nearly continuously, since celestial references are used only during star scan maneuvers once every orbit or two. Other spacecraft are designed to use celestial reference nearly continuously, and they rely on gyroscopes for their attitude reference only during relatively short maneuvers when celestial reference is lost. In either case, gyro data must be taken with a grain of salt; today's gyroscopes are mechanical, so they precess and drift due to internal friction. Great pains are taken to calibrate their rates of drift, so that the AACS may compensate for it when it computes its attitude knowledge.

AACS also controls the articulation of a spacecraft's moveable appendages such as solar panels, high-gain antennas, de-spun components, or optical instrument scan platforms. The AACS is a likely candidate for doing this because it keeps track of the spacecraft's attitude, the sun's and Earth's locations, and it can compute the direction to point the appendages.

Telecommunications Subsystems

This section deals specifically with telecommunications equipment on board a spacecraft. A broader view of the whole telecommunications system, including Earth-based components may be found in Chapter 10.

Telecommunications subsystem components are chosen for a particular spacecraft in response to the requirements of the mission profile. Anticipated maximum distances, planned frequency bands, data rates and available on-board transmitter power are all taken into account. Each of the components of this subsystem is discussed below:

High-Gain Antennas

Dish-shaped high-gain antennas (HGAs) are the spacecraft antennas principally used for communications with Earth. The amount of gain achieved by an antenna (indicated in this workbook as high, low, or medium) refers to the amount of incoming radio power it can collect and focus into the spacecraft's receiving subsystems. In the frequency ranges used by spacecraft, this means that HGAs incorporate large paraboloidal reflectors. The cassegrain arrangement, described in Chapter 6, is the HGA configuration used most frequently aboard interplanetary spacecraft. Ulysses, which uses a prime focus feed, is one exception.

HGAs may be either steerable or fixed to the spacecraft bus. The Magellan HGA, which also served as a radar antenna for mapping (and as a drogue for aerobraking), was not articulated; the whole spacecraft had to be maneuvered to point the HGA to Earth for communications.

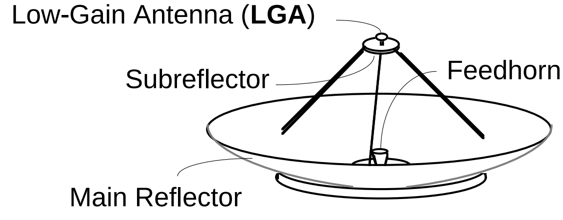
Magellan's HGA, by the way, also served as a fine sunshade. Mission ops people routinely pointed it to the sun in order to provide some needed shade for the rest of the spacecraft.

The Mars Global Surveyor HGA is on an articulated arm to allow the antenna to maintain Earth-point independent of the spacecraft's attitude while it maps the surface of Mars. Galileo's HGA was designed to unfold like an umbrella after launch. This enabled the use of a larger diameter antenna than would have fit in the Space Shuttle cargo bay if a fixed antenna had been chosen. However, the project has been unable to fully deploy the antenna, thus severely limiting communications with the spacecraft. Efforts to overcome this problem have not met with success, and the project is carrying out the mission using Galileo's low gain antennas constrained to low data rates. Now onboard software and improvements in the DSN will permit recovery of 70% of the originally planned science data.

The larger the collecting area of an HGA, the higher the gain, and the higher the data rate it will support. The higher the gain, the more highly directional it is. When using an HGA, it must be pointed to within a fraction of a degree of Earth for communications to be feasible. Once this is achieved, communications may take place at a high rate over the highly focused radio signal. This is analogous to using a telescope, which provides magnification (gain) of a weak light source, but it requires accurate pointing. No magnification is achieved with the naked eye, but it covers a very wide field of view, and need not be pointed with great accuracy to detect a source of light, as long as it is bright enough. In case AACS fails to be able to point a spacecraft's HGA with high accuracy for one reason or another, there must be some other means of communicating with the spacecraft.

Low-gain Antennas

Low-gain antennas (LGAs) provide wide-angle coverage (the "naked-eye," to continue the analogy) at the expense of gain. Coverage is nearly omnidirectional, except for areas that may be shadowed by the spacecraft body. LGAs are designed to be useable for relatively low data rates, as long as the spacecraft is within relatively close range, several AU for example, and the DSN transmitter is powerful enough. Magellan could use its LGA at Venus's distance, but Voyager must depend on its HGA since it is over 40 AU away. Some LGAs are mounted atop the HGA's subreflector, as in the following diagram. This is the case with Voyager, Magellan, and Galileo. A second LGA, designated LGA 2, was added to the Galileo spacecraft in the redesign which included an inner-solar system gravity assist. LGA-2 faces aft, providing Galileo with fully omnidirectional coverage by accommodating LGA-1's blind spots.



High-Gain Antenna (HGA)

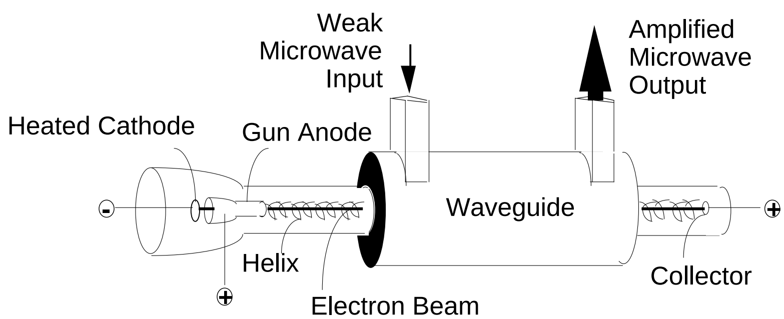
Medium-gain Antennas

MGAs are a compromise, providing more gain than an LGA, with wider angles of pointing coverage than an HGA, on the order of 20 or 30 degrees. Magellan carried an MGA consisting of a large cone-shaped feed horn, which was used during some maneuvers when the HGA is off Earth-point.

Spacecraft Transmitters

A transmitter is an electronic device which generates a tone at a single designated radio frequency, typically in the S-band (~2 GHz) or X-band (~5 GHz) range. This tone is called the carrier. The carrier can be sent from the spacecraft to Earth as it is, or it can be modulated with a data carrying subcarrier within the transmitter. The signal generated by the spacecraft transmitter is passed to a power amplifier, where its power is boosted to the neighborhood of tens of watts. This microwave-band power amplifier may be a solid state amplifier (SSA) or a traveling wave tube (TWT, also TWTA, pronounced "tweeta," for TWT Amplifier). A TWTA uses the interaction between the field of a wave propagated along a waveguide, and a beam of electrons traveling along with the wave. The electrons tend to travel slightly faster than the wave, and on the average are slowed slightly by the wave. The effect amplifies the wave's total energy.

Travelling Wave Tube Amplifier



The output of the power amplifier is ducted through waveguides and commandable waveguide switches to the antenna of choice: HGA, MGA, or LGA.

Spacecraft Receivers

Commandable waveguide switches are also used to connect the antenna of choice to a receiver. The receiver is an electronic device that is sensitive to a narrow band of frequency, generally a width of plus and minus a few kHz of a single frequency selected during mission design. Once an uplink is detected within its bandwidth, the receiver's phase lock-loop circuitry (PLL) will follow any changes in the uplink's frequency within its bandwidth. JPL invented PLL technology in the early 1960s, which has since become standard in the telecommunications industry. The receiver can provide the transmitter with a frequency reference keyed to the received uplink. The received uplink, once detected, locked onto, and stepped down in frequency, is stripped of its command-data-carrying subcarrier, which is passed to circuitry called a command detector unit (CDU). This unit converts the analog phase-shifts which were modulated onto the uplink's subcarrier into binary 1s and 0s, which are then typically passed to the spacecraft's CDS.

Frequently, transmitters and receivers are combined into one electronic device which is called a transponder.

Recap

1. When using an ___ ___ ___ , it must be pointed to within a fraction of a degree of Earth.
2. LGA coverage is nearly ____________________ , except for areas shadowed by the spacecraft body.
3. The output of the ______________ _______________ is ducted through waveguides and commandable waveguide switches to the antenna.
4. The receiver's _____________ - ____________ - ___________ circuitry will follow any changes in the uplink's frequency.

1. HGA   2. omnidirectional   3. power amplifier   4. phase-lock loop

Electrical Power Supply and Distribution Subsystems

Roughly between 300 W and 2.5 kW of electricity is required to power a spacecraft the likes of Voyager, Galileo, or Magellan. The power supply must provide a large percentage of its rated power over a lifetime measured in years or decades. Choices of technology to meet these requirements are constrained largely to two: photovoltaics and radioisotope thermo-electric generators (RTGs).

Photovoltaics

As the term suggests, photovoltaic materials convert light to electricity. Crystalline silicon and gallium arsenide are typical choices of materials for deep-space applications. Gallium arsenide crystals are grown especially for photovoltaic use, but silicone crystals are available in less-expensive standard ingots which are produced mainly for consumption in the microelectronics industry.

When exposed to direct sunlight at 1 AU, a current of about an ampere at 0.25 volt can be produced by a 6-cm-diameter silicon cell. Gallium arsenide is notably tougher and more efficient. Crystalline ingots are sliced into wafer-thin circles, and metallic conductors are deposited onto each surface: a thin grid on the sun-facing side and a flat sheet on the other. Spacecraft solar panels are constructed of these cells trimmed into appropriate shapes and cemented onto a substrate, and electrical connections are made in series-parallel to determine total output voltage. The cement and the substrate must be thermally conductive, because in flight the cells absorb a lot of infra-red energy and want to reach high temperatures. They are more efficient when kept to lower temperatures. The resulting assemblies are called solar panels or solar arrays.

Solar power is practical for spacecraft operating no farther from the sun than about the orbit of Mars. Magellan and Mars Observer used solar power, as will Mars Global Surveyor and Pathfinder. Topex/ Poseidon, the Hubble Space Telescope, and most other Earth orbiters use solar power. The solar panels must be aimed so that they may be maintained at optimum sun point, and they may be off-pointed slightly for periods when it may be desirable to generate less power.

Prolonged exposure to sunlight causes photovoltaics' performance to degrade in the neighborhood of a percent or two per year, and more rapidly if exposed to particle radiation from solar flares.

Radioisotope Thermoelectric Generators

Radioisotope thermoelectric generators (RTGs), are used when spacecraft must operate at significant distances from the sun (usually beyond the orbit of Mars),or where the availability of sunlight and therefore the use of solar arrays is otherwise infeasible. RTGs as currently designed for space missions contain several kilograms of an isotopic mixture of the radioactive element plutonium in the form of an oxide, pressed into a ceramic pellet. The primary constituent of these fuel pellets is isotope 238 (Pu-238). The pellets are arranged in a converter housing and function as a heat source to generate the electricity provided by the RTG. The radioactive decay of the plutonium produces heat, some of which is converted into electricity by an array of thermocouples made of silicon germanium junctions. Waste heat is radiated into space from an array of metal fins.

Plutonium, like all radioactive materials and many non-radioactive materials, can be a health hazard under certain circumstances and in sufficient quantity. RTGs are designed, therefore, with the goal of surviving credible launch accident environments without releasing plutonium. The safety design features of RTGs are tested by the US Department of Energy to verify the survival capabilities of the devices.

Presidential approval is required for the launch of RTGs. Prior to the launch of a spacecraft carrying an RTG, a rigorous safety analysis and review is performed by the Department of Energy, and the results of that analysis are evaluated by an independent panel of experts. These analyses and reviews are used by the Office of Science and Technology Policy (OSTP) in the White House to evaluate the overall risk presented by the mission.

RTGs must be located on the spacecraft in such a way as to minimize their impact on particle-detecting or infra-red detecting science instruments. Galileo's RTGs are mounted behind shields to shade the near-infrared mapping spectrometer from their thermal radiation. Much of the spacecraft's mass shields Galileo's high-energy particle detector instrument from the RTG's gamma radiation.

RTGs performance degrades in flight about one to two percent per year, which is slightly faster degradation than for photovoltaics.

Electrical Power Distribution

Virtually every electrical or electronic component on a spacecraft may be switched on or off via command. This is accomplished using solid-state or mechanical relays which connect or disconnect the component from the common distribution circuit, called a main bus. On some spacecraft, it is necessary to power off some set of components before switching others on, in order to keep the electrical load within the limits of the supply. Voltages are measured and telemetered from the main bus and a few other points in the electrical system, and currents are measured and telemetered for many individual spacecraft components and instruments to show their consumption.

Typically, a shunt-type regulator maintains a constant voltage from the power source. The voltage applied as input to the shunt regulator is generally variable but higher than the spacecraft's required constant bus voltage. The shunt regulator converts excess electrical energy into heat, which is radiated away into space via a radiating plate. On spacecraft equipped with articulating solar panels, it is sometimes possible, and desirable for reasons of spacecraft thermal control, to off-point the panels from the sun to reduce the regulator input voltage, and thus reduce the amount of heat generated by the regulator.

Electrical Power Storage

Spacecraft that use photovoltaics usually are equipped with rechargeable batteries, which receive a charge from the main bus when the solar panels are in the sunlight, and discharge into the bus to maintain its voltage whenever the solar panels are shadowed by the planet or off pointed during spacecraft maneuvers. Nickel-cadmium batteries are frequently used. After hundreds of charge-discharge cycles, this type of battery degrades in performance, but may be rejuvenated by carefully controlled deep discharge and recharge, an activity called reconditioning.

Recap

1. Roughly between ____________ and __________ of electricity is required to power a spacecraft the likes of Voyager, Galileo, or Magellan.
2. __________________________ materials convert light to electricity.
3. In RTGs... thermal radiation is converted directly into electricity by an array of ____________________ made of silicon-germanium junctions.
4. The shunt regulator converts excess electrical energy into ________________, which is radiated away into space.

1. 300 W and 2.5 kW 2. photovoltaic 3. thermocouples 4. heat

Environmental Subsystems

Passive Cooling

Active cooling systems are generally not practical on interplanetary spacecraft. Instead, painting, shading, and other techniques provide efficient passive cooling. Internal components will radiate more efficiently if painted black, helping to transfer their heat to the outside. White thermal blankets reflect IR, helping to protect the spacecraft from excess solar heating. Gold is a very efficient IR reflector, and is used to shade critical components. Optical solar reflectors (OSRs), which are quartz mirror tiles, may be used for the same purpose. They were used extensively on Magellan, including the back side of solar panels. Mechanical louvers are frequently used to control thermal radiation from within parts of a spacecraft. Bi-metallic strips, not unlike the ones in a wall thermostat, mechanically open or close the louvers to retain or release IR.

Active Heating

Resistive electric heaters, controlled either autonomously or via command, are applied to various components to keep them above their minimum allowable temperatures. Radioisotope heaters, typically containing small amounts of plutonium, are installed where necessary to provide components with a permanent supply of heat.

Micro-meteoroid Protection

Tough blankets made with Kevlar or other strong fabrics cover interplanetary spacecraft to absorb the energy from high-velocity micro meteoroids before they can do any damage to spacecraft components. These hazards are greatest when crossing the ring planes of the Jovian planets. Voyager recorded thousands of hits in these regions, fortunately from particles about the size of particles of smoke. Spacecraft sent to comets, such as Giotto, carry massive shields to protect from hits by larger particles.

Jovian Radiation

Bringing a spacecraft into close proximity to Jupiter presents a radiation hazard mostly from ionized particles in the Jovian environment. Spacecraft designed to carry out observations at Jupiter must be designed with radiation-hardened components and shielding. Spacecraft using Jupiter for a gravity-assist course correction are also exposed to a harsh radiation dose. Instruments not intended to operate at Jupiter must be protected by being powered off and by having detectors covered. Components on such a spacecraft must be selected with the Jovian environment in mind.

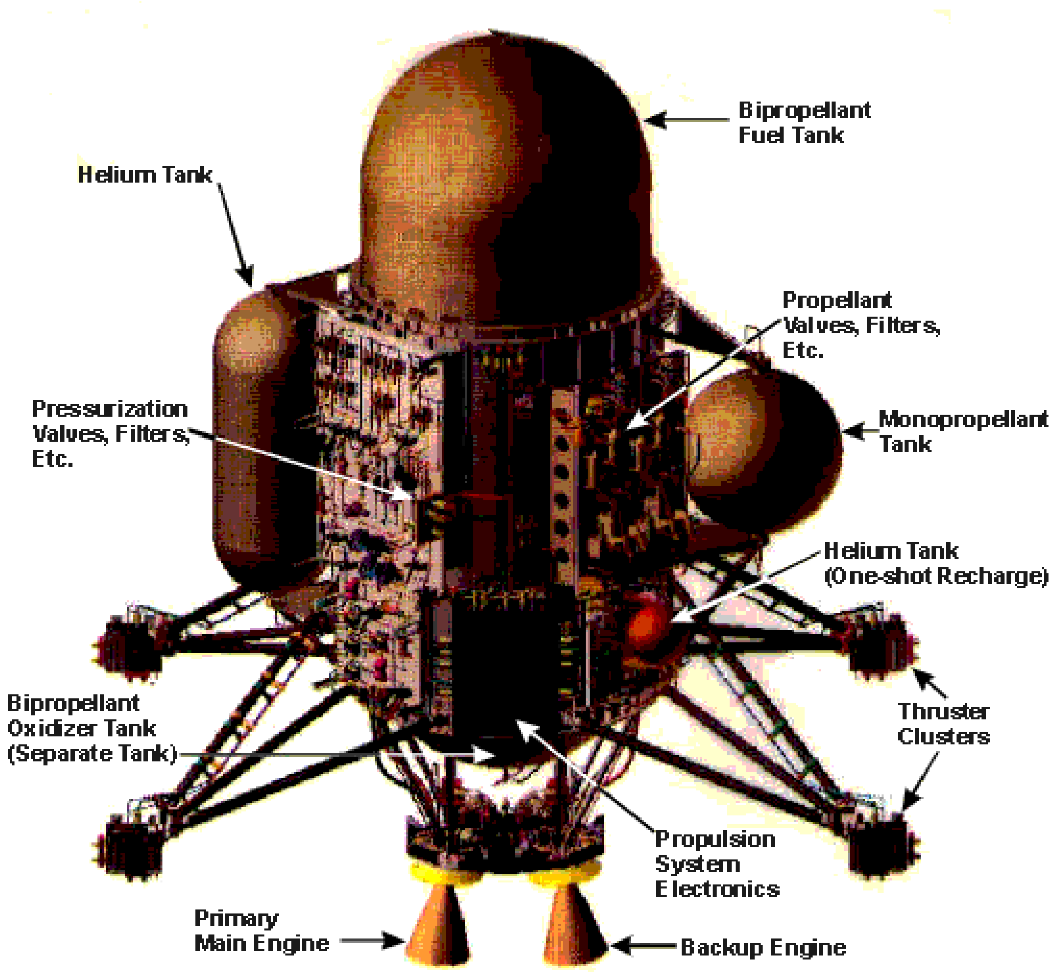
Propulsion Subsystems

In order to maintain or restore three-axis stability, to control spin, to execute maneuvers and make minor adjustments in trajectory, spacecraft are provided with sets of propulsive devices. The more powerful devices are usually called engines, and they may provide a force of several hundred Newtons. These may be used to provide the large torques necessary to maintain stability during a solid rocket motor burn, or they may be the only rockets used for orbit insertion.

The set of smaller devices, generating between less than 1 N and 10 N, are typically used to provide the delta-V for interplanetary trajectory correction maneuvers, orbit trim maneuvers, reaction wheel desaturation maneuvers, or routine three-axis stabilization or spin control.

Other components of propulsion subsystems include propellant tanks, plumbing circuits with electrically or pyrotechnically operated valves, and helium tanks to supply pressurization for the propellant tanks. Some propulsion subsystems, such as Galileo’s, use hypergolic propellants—two compounds stored separately which ignite spontaneously upon being mixed in the engines or thrusters. Other spacecraft use hydrazine, which decomposes explosively when brought into contact with an electrically heated metallic catalyst within the engines or thrusters. Cassini, whose propulsion system appears in the following diagram, uses both hypergolics and hydrazine monopropellant. Many of the activities of propulsion subsystems are routinely initiated by AACS. Some or all may be directly controlled by or through CDS.

Cassini's Propulsion System



Pyrotechnic Subsystems

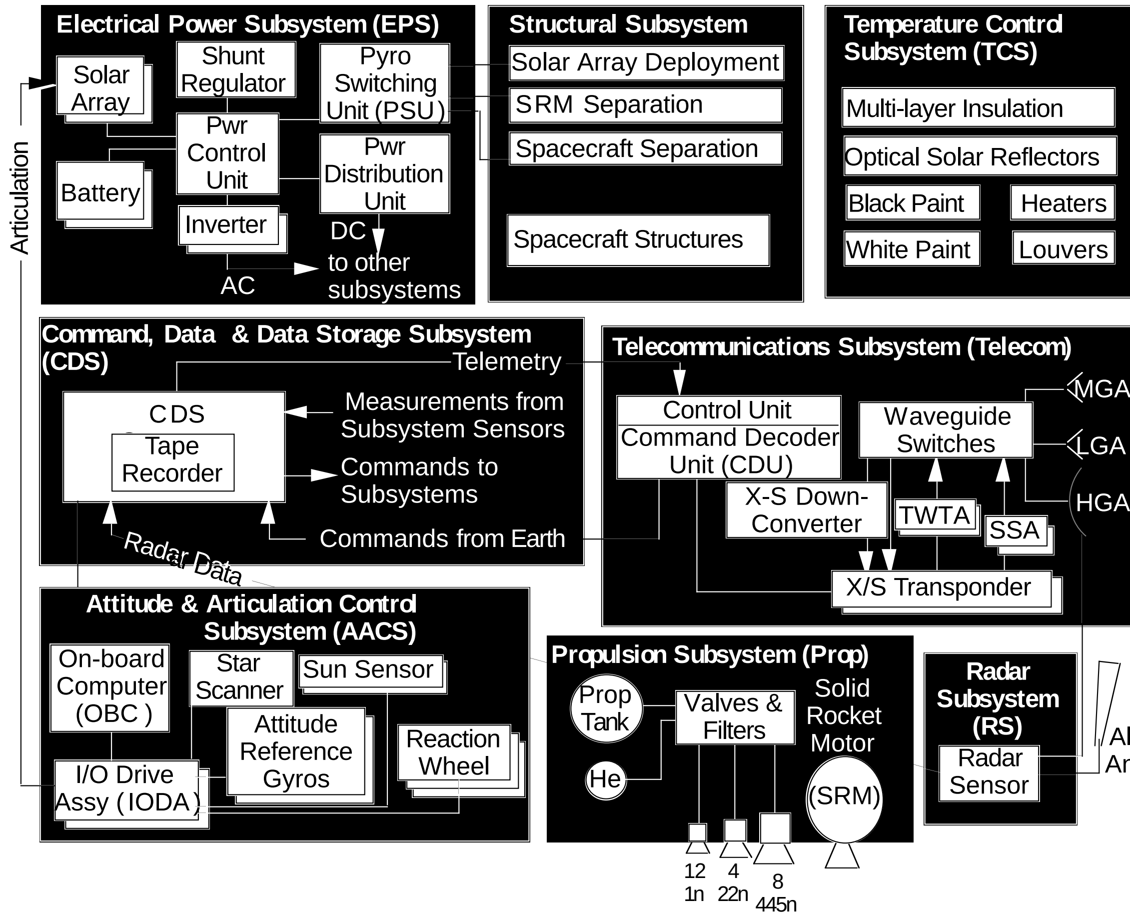
Electrically initiated pyrotechnic devices are used to operate certain valves, ignite solid rocket motors, and explode bolts to separate from or jettison hardware, or to deploy appendages. They obtain their electrical power from a bank of capacitors which are charged from the main bus several minutes prior to the planned detonation of a device. Typically called a pyrotechnic switching unit (PSU), this device helps to insure successful initiation of the pyrotechnic device, and also protects the main bus from a momentary power drain when a pyro device is activated.

Block Diagram Illustration

The block diagram on the next page illustrates the combination of many of the subsystems discussed in this chapter into a space flight system, the Magellan spacecraft. Magellan carried only one science instrument, the Radar Subsystem, depicted in the lower right. Otherwise, the spacecraft had many subsystems which are typical of those found on many other spacecraft.

Boxes within the diagram are shown double or triple, to indicate the presence of two or three units of the same name. The numbers 12, 4, and 8 below the rocket engines indicate the quantity of each kind installed.

Block Diagram of Magellan Space Flight System



Redundancy and Flexibility

The hallmark of modern automated spacecraft is flexibility: the ability to maintain or restore functionality after component failure, or to increase or extend functionality based on newly conceived techniques. Components fail unexpectedly during the life of a mission. Most of those upon which the success of the mission depends have redundant backups, and the means to reroute functional flow to accommodate their use either autonomously or via commanding in real time. Several spacecraft continue to operate today, such as Voyager and Pioneer, returning valuable science data long after their primary missions have been completed, thanks entirely to the on-board availability of redundant transmitters, receivers, tape recorders, gyroscopes, antennas, and the all-important ability to modify on-board flight software.

Advanced Technologies

Ongoing research at JPL and other institutions is producing new technologies for less costly and more capable, reliable and efficient spacecraft for future space missions throughout and beyond the solar system. Advances in such areas as spacecraft power, propulsion, communications, data handling systems, pointing control and materials is expected to increase by factors of 10 to 1000 the potential science returns from future missions.

The Space Power-100 (SP-100) Project at JPL is developing key components of a nuclear reactor power system for use in planet and asteroid exploring missions. An array of thermocouples converts heat from the reactor to provide more than 25 times the power of a typical RTG.

Once outside Earth's atmosphere and in freefall, solar-powered electric drives, or nuclear-powered electric drive systems, can be used to accelerate spacecraft. Ion engines produce thrust when a electrically charged propellant, such as xenon, is accelerated through a nozzle to a typical velocity of 50 km/sec. These electric engines use much less propellant than the most advanced chemical engines. With their high nozzle exit velocities, they can permit spacecraft to achieve the high velocities required for interplanetary or interstellar flight. Solar sails, which use solar radiation pressure in much the same way that a sailboat uses wind, may also provide a means for high-speed interplanetary or interstellar propulsion.

Another JPL research effort is developing an Autonomous Star Tracker to identify guide stars for more robust methods of attitude determination and recovery from loss of orientation. They may also provide instruments with the capability to track points of interest easily and eliminate the need for tedious mosaicking and overlapping of images.

Telecommunications systems are being developed to operate in K and Ku bands, higher frequencies than the current S- and X-band systems. Laser telecommunications systems are also being developed which modulate data onto beams of coherent light instead of radio. Among the advantages to laser telecom are low power consumption, much higher data rates, and reduced-aperture Earth stations. The pointing requirements for laser communication are much more stringent than for microwave radio communication. During Galileo's Earth-2 flyby enroute to Jupiter, JPL succeeded in transmitting laser signals to Galileo, which received them as points of light detected by the Solid State Imaging System (SSI). Additional experiments are being planned for Space Shuttle missions to transmit data by laser at very high rates, overcoming interference from sunlight.

Laser gyroscopes are being developed which replace the moving components of mechanical gyroscopes, which are very susceptible to wear, with kilometer-lengths of fiber optic coils, using the Doppler shift of light moving through them to sense spacecraft rotation rates.

The Thousand AU mission (TAU) previously under study at JPL, has been funded from the Director's discretionary fund. Its mission is to use many of these advanced technologies to fly a spacecraft to a distance of one thousand AU within 50 years flight time. Its objective would be to make measurements of stellar parallax, providing the next generation of astronomers a new dimension of data on stellar distances within our galaxy.

Recap

1. Mechanical _______________ are frequently used to control thermal radiation from within parts of a spacecraft.
2. __________________ propellants are two compounds stored separately which ignite spontaneously upon being mixed in the engines or thrusters.
3. Most components... upon which the success of the mission depends have redundant _________________ .
4. Laser ______________________ systems are being developed which modulate data onto beams of light instead of radio.

1. louvers *2. Hypergolic* *3. backups* *4. telecommunications*

This fold-out illustration of the Galileo Jupiter orbiter spacecraft, with its atmospheric probe, serves as an illustration to Chapters 11 and 12.

The Galileo Spacecraft

Science experiments are described in italics, and have blue connecting lines. Engineering components are shown with red connecting lines.

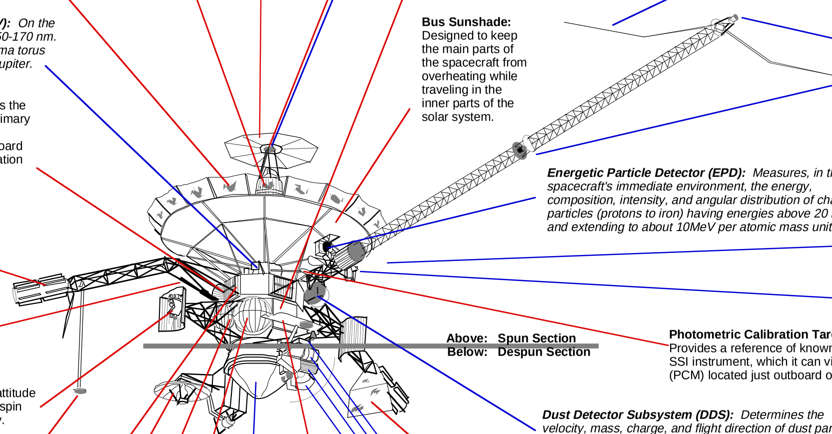
Spacecraft Spun Section: The spun bus houses electronics and computers for attitude control, command processing, and flight science data processing. Also houses components such as radios, data storage tape recorder, and support systems.

Retro Propulsion Module (RPM): The entire propulsion system is a single module provided by the Federal Republic of Germany. It consists of twelve 10N attitude control thrusters on two A/C thruster booms, one central 400N thruster, four tanks of fuel and oxidizer, and two tanks of helium pressurant. The HGS, RTGs, and Science Boom are also part of the spun section.

Spin Bearing Assembly (SBA): Connects the spun and the despun sections of the spacecraft. In addition to mechanical coupling, 48 slip-rings provide transfer of power and low-rate data, and rotary transformers provide a coupling for high-rate data. An optical encoder provides relative position information.

Spacecraft Despun Section: The scan platform and its optical instruments and the probe radio relay hardware are despun via the SBA so they can be pointed at their targets. The atmospheric probe is carried as part of the despun section.

Spacecraft Spin: The spun section turns about the roll axis at roughly 3 RPM in its normal, dual-spin mode. During the probe release maneuver and the Jupiter orbit insertion maneuver, the entire spacecraft spined together at about 10 RPM. Spin direction is indicated at left.



Reflector Structure: Part of the high-gain antenna which focuses and feeds the incoming and outgoing radio signals.

HGA Sunshade: Designed to protect the High-gain Antenna (when furled) from direct solar radiation while traveling in the inner parts of the solar system.

High-gain Antenna (HGA): Consists of a deployable reflector dish 4.8 m in diameter (similar to those on the TDRSS earth satellites), and a reflector/feed structure supported above it. Designed to suport a communications rate of 134 kbps, the HGA has not been able to unfurl due to an anomaly, and is currently unusable. (Shown in its deployed configuration, which has not been achieved.)

Extreme Ultraviolet Spectrometer (EUV): *On the spun bus, is sensitive to wavelengths of 50-170 nm. Investigates emmissions from the Io plasma torus and auroral and airglow phenomena on Jupiter.*

Star Scanner: Observes stars as the spacecraft spins, providing the primary reference for the Attitude Control Computer which refers to an onboard star catalog for attitude determination (partly hidden in this view.)

Radioisotope Thermoelectric Generators (RTGs): Produce a supply of roughly 500 watts of electricity from banks of thermocouples heated by the decay of radioactive material.

Linear Boom Actuator (LBA): On each RTG boom. Extends or contracts on command to allow minute adjustments in the RTG boom's angle, for minimizing spacecraft wobble.

A/C Thrusters: Two groups of size 10N attitude control thrusters are used for attitude and spin changes and small adjustments to velocity.

Low-gain Antenna 2 (LGA2): Used for communication with the high-gain antenna furled, while the spacecraft is pointing generally away from Earth.

Temperature Control Louvers: Mechanical devices that open and close automatically to control radiation of heat from within the spacecraft.

Radio Relay Hardware (RRH): Antenna and electronics tracked and received data from the atmospheric probe during its short operational life descending into Jupiter's atmosphere. These data were relayed to Earth via the LGA.

Helium Tank: Provides helium to pressurize the fuel and oxidizer tanks.

Fuel and Oxidizer Tanks: Together, the four titanium-alloy tanks contained about 960kg of propellant at launch. The hypergolic fuel and oxidizer ignite spontaneously when brought together in the RPM's attitude control thrusters and main engine.

Atmospheric Probe: *Descended into Jupiter's atmosphere to make in-situ measurements. Includes instruments to measure temperature, pressure, and deceleration; a neutral mass spectrometer determines chemical composition; an interferometer determines helium abundance; a nephelometer observes cloud particles; a net-flux radiometer measures the difference between upward and downward radiant energy. Also on board are an energetic particle detector, lightning, and radio-emission detectors. In addition, the radio link with the Orbiter provided Doppler wind data. The Probe separated from the Orbiter in July 1995, and successfully completed its mission on December 7, 1995.*

Low-gain Antenna 1 (LGA1): Used for communication while the spacecraft is pointing generally toward Earth. Radio signals are modulated to carry telemetry from the spacecraft to Earth at up to 100 bits per seconds, and commands from Earth to the spacecraft. In addition, these signals are used for precisely tracking the spacecraft's speed, distance, and angular position.

Propellant Control Assembly (PCA): Valves, tubing, pressurization and feed controls, and other propulsion system components are located on these two rectangular panels.

Bus Sunshade: Designed to keep the main parts of the spacecraft from overheating while traveling in the inner parts of the solar system.

Radio Science: *The spacecraft can transmit unmodulated, precise-frequency (near 2.3 GHz) microwave radio signals for experiments that directly yield information about rings and atmospheres, mass distribution, celestial mechanics, and general relativity. A gravitational wave search was conducted during cruise. Investigations of the solar corona are conducted near superior conjunction.*

Plasma Wave Subsystem (PWS): *Uses a dipole antenna composed of two 10m graphite-epoxy antennas at the tip of the magnetometer boom, and search coils in the HGA reflector structure. Measures electrostatic and electromagnetic components of plasma waves in three dimensions.*

Magnetometers: *Sense magnetic fields in the spacecraft's immediate environment, as well as distortions in those fields due to interactions with satellites or plasma. They are located as far as possible from magnetic interference aboard the spacecraft, on a fiberglass boom 10.9 m long.*

Energetic Particle Detector (EPD): *Measures, in the spacecraft's immediate environment, the energy, composition, intensity, and angular distribution of charged particles (protons to iron) having energies above 20 keV and extending to about 10MeV per atomic mass unit.*

Heavy Ion Counter (HIC): *On top of Bay 2 (not visible in this view) provides data on collisions with ionized atoms (carbon through nickel) trapped in the Jovian magnetic field which may have the potential to cause damage to spacecraft.*

Plasma Instrument (PLS): *Measures the composition, energy, temperature, density, and three-dimensional distribution and bulk motions of low-energy plasma (ions) in the spacecraft's immediate environment. Range is from 1V to 50kV, with 5-second temporal resolution.*

Photometric Calibration Target (PCT): Provides a reference of known conditions for the SSI instrument, which it can view in a mirror (PCM) located just outboard on the boom.

Dust Detector Subsystem (DDS): *Determines the velocity, mass, charge, and flight direction of dust particles in interplanetary space and the Jovian system. Sensitive to dust particle mass of 10^{-16} to 10^{-6}g. Up to 100 particles per second can be detected.*

RTG Shields: Shade the hot RTGs, a source of infrared energy, from the NIMS instrument to prevent interfering with its observations.

Scan Platform: Can be commanded to point its four optical, remote-sensing instruments in specified directions. Instruments on scan platform include:

Ultraviolet Spectrometer (UVS): *On the scan platform, measures gases and aerosols in the Jovian atmosphere and searches for complex molecules. Sensitive to wavelengths of 1150 to 4300 Angstroms.*

Solid State Imaging (SSI): *1500mm telescopic camera on the scan platform provides high-resolution images in visible light. The sensor is an actively-cooled, tantalum-shielded Charge-Couple Device (CCD) of 800 x 800 pixels. Color pictures are obtained by combining images taken through different filters. The instrument's best observations will detect objects as small as about 20 m.*

Near-Infrared Mapping Spectrometer (NIMS): *On the scan platform, measures the thermal, compositional, and structural nature of its targets. Sensitive to wavelengths of 0.7 to 5 microns.*

Photopolarimeter Radiometer (PPR): *On the scan platform, combines a photometer, a polarimeter, and a radiometer to observe light in visible and infrared wavelengths. Provides data on atmospheric composition and thermal energy distribution (not visible behind NIMS in this view).*

Scan Platform Sunshade: Protects the scan platform instruments from direct sunlight during its inner solar system flight. Also supports calibration targets for the NIMS and PPR instruments. The PPR target is the cone-shaped feature pointing down near the edge.

Thermal Blanketing which covers much of the spacecraft for the purpose of temperature control and micrometeroid protection is not depicted (with the exception of the sunshades).