7 Spacecraft Design

Basic Spacecraft Design Method

IN this and the next couple of chapters, we discuss how spacecraft are designed, and what physical factors influence (or drive) the design of the major elements that make up the vehicle. These major elements are referred to as *subsystems*. The process of spacecraft design is all about how these elements are designed and how they are integrated to produce a total spacecraft system capable of achieving the mission objectives and of surviving the damaging features of the space environment that we cited in the last chapter.

Orbit selection was discussed in Chapter 2, and the logic of the method used there is relevant to our discussion now. To review briefly, the process begins with the definition of the spacecraft's *mission objective*, the formulation of a precise statement defining the prime purpose of the spacecraft. This might be something like "the provision of high-resolution imagery of Earth with global coverage," for example. The next step is to choose the *payload instruments* or equipment required to achieve the objective; in this example it would be the cameras required to produce the images of the ground from orbit. The third step is the development of a *payload operational plan:* How does the payload hardware need to operate to best achieve the objective? In Chapter 2, when we discussed orbits, these requirements included where the payload needed to be physically located to maximize its effectiveness, which led naturally to the selection of an appropriate mission orbit—a near-polar low Earth orbit (LEO) in this case. However, this same logic also leads us to the requirements for the design of the subsystem elements of the spacecraft.

The payload is the most important part of the spacecraft; without it, the objectives of the mission cannot be achieved. The subsystems are there purely to support the payload in its operation. Thus the design of each subsystem is driven by what it needs to do and what resources it needs to provide to ensure that the payload does its job effectively. For example, the payload will need a certain amount of electrical power to operate, and so the

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design of the electrical power subsystem—the size of the solar panels and batteries on board—is governed by this payload requirement. And this type of logic extends to define the design requirements for all the other subsystems as well.

We have mentioned the spacecraft's subsystems but we have not defined them and explained what they do. All spacecraft are comprised of these basic subsystem elements, and Table 7.1 lists the main ones and the functions they fulfill in supporting the payload in its operation.

Table 7.1: The main spacecraft subsystem elements and their function

Subsystem	Function
Payload	To fulfill the mission objective, using appropriate payload hardware (e.g., camera, telescope, communications equipment—depending upon the objective).
Mission analysis	To select the launch vehicle that will launch the spacecraft, to select the best orbit for the spacecraft to achieve the objectives of its mission, and to determine how the spacecraft will be transferred from launch pad to final orbital destination.
Attitude control	To achieve the spacecraft's pointing mission (e.g., to point a payload telescope at a distant galaxy, to point a solar panel to the Sun to raise electrical power, to point a communications dish at a ground station)
Propulsion	To provide a capability to transfer the spacecraft between orbits, and to control the mission orbit (see Chapter 3) and the spacecraft attitude (see Chapter 8), using on-board rocket systems
Power	To provide a source of electrical power to support payload and subsystem operation
Communications	To provide a communications link with the ground, to downlink payload data and telemetry, and to uplink commands to control the spacecraft
On-board data handling	To provide storage and processing of payload and other data, and to allow the exchange of data between subsystem elements
Thermal control	To provide an appropriate thermal environment on board, to ensure reliable operation of payload and subsystem elements
Structure design	To provide structural support for all payload and subsystem hardware in all predicted environments (especially the harsh launch vehicle environment)

A few comments on Table 7.1: First, some engineers prefer not to classify the payload as a subsystem. They like to divide the spacecraft into two parts, and distinguish the payload from the spacecraft *platform* (or service module), the latter being the part of the vehicle containing all of the supporting subsystems. Second, mission analysis is sometimes not considered to be a subsystem, as there is no piece of hardware on board the vehicle that can be identified with this. However, I have included both payload and mission analysis in the table to reflect the structure of a typical spacecraft project design team (see next section). As we will see, all the areas in Table 7.1 are represented by design engineers in such a team, as they all have a profound influence on the overall design process. Third, *telemetry* is mentioned in the table in the communications subsystem section. This is essentially health-monitoring data, generated on board the spacecraft by sensors distributed around the vehicle. These sensors check the state of the spacecraft's components and issue a warning if problems occur. These data are down-linked as telemetry to the spacecraft operations room and are displayed on the operators' computer screens, so that action can be taken if trouble arises.

We can summarize the process described so far with the block diagram in Figure 7.1. Starting with the mission objective at the top and working down, we can decide what payload instruments we need, and how they are to be operated to achieve the objective. Then, once we have the payload, we can look at the resources it needs from the subsystems to operate successfully. Referring to Figure 7.1, the payload will require a particular amount of electrical power, for example, and this will lead to the design of the power subsystem (obviously, the subsystems will also need electrical power to operate, and so in this case the power subsystem design is not just dictated by the payload interface). If the payload requires pointing, such as a telescope or an Earth-observation imaging camera, then the accuracy and stability of pointing will govern the design of the attitude control subsystem. The payload will also generate data, perhaps in the form of pictures from an imaging payload. These data will either be stored on board or transferred directly to the communications subsystem for down-linking to the ground. The rate at which the payload generates the data, and the overall amount of data, will govern the design of the on-board data handling (OBDH) subsystem, which deals with these processes. The data rate generated by the payload then needs to be down-linked by the communications subsystem over large distances to a receiving ground station, and again this leads to the design requirements for the spacecraft's communications subsystem. Also, certain payloads may have to be maintained within a strict temperature range to work properly, and this will govern how the thermal control subsystem is designed.

The design of the subsystems is also influenced by other factors. In

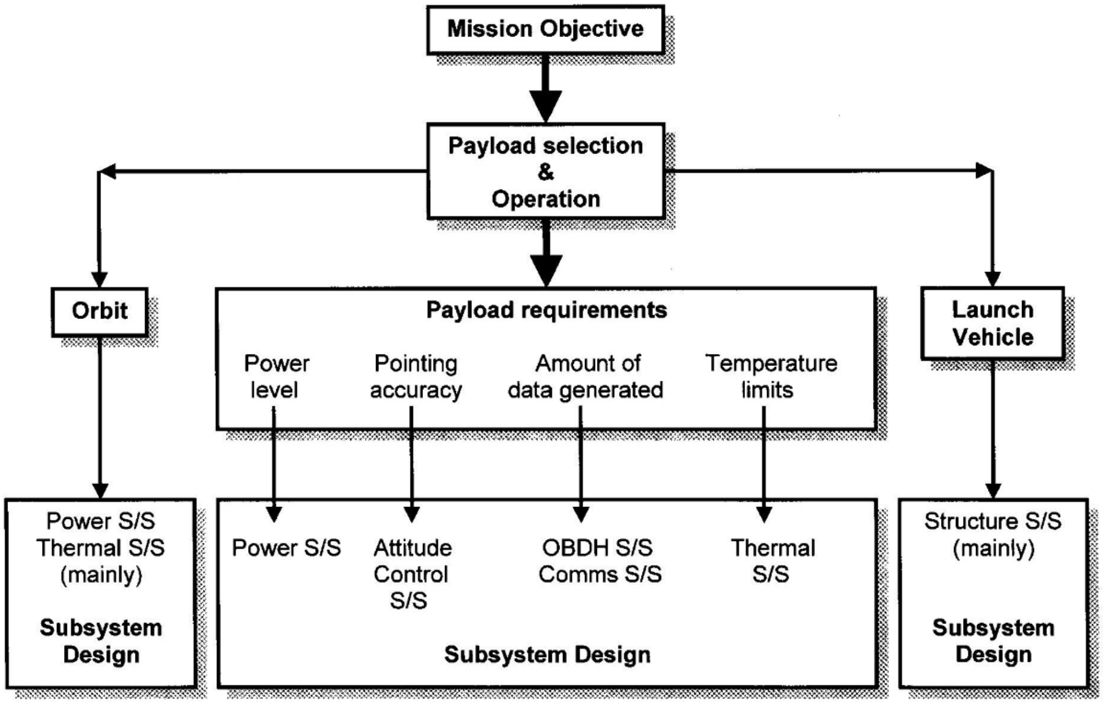

Figure 7.1: A block diagram showing how the spacecraft subsystems are designed. Note: OBDH, on-board data handling; S/S, subsystem.

Chapter 2 we saw how the payload operation led to the choice of mission orbit for the spacecraft, and this is indicated on the left-hand side of Figure 7.1. It is also the case that the orbit itself impacts on the design of the subsystems. For example, once the orbit is specified, the mission analysts can calculate the eclipse period for the spacecraft, which is the time that the spacecraft spends in darkness on each orbit revolution of the Earth. If the satellite is using solar panels to generate electricity during the sunlit part of the orbit, and batteries otherwise, then the design of these components of the power subsystem is greatly influenced by eclipse period of the mission orbit. Similarly, the eclipse period will dictate the amount of direct solar heating (and cooling while in darkness) the spacecraft will encounter on each orbit, which in turn will affect the thermal control subsystem design.

We saw in Chapter 5 how the harsh environment of the launch vehicle was the most influential input to the structure design of the spacecraft, and this is shown on the right-hand side of the Figure 7.1. The design method is not at all mysterious, and is basically applied common sense!

The Spacecraft Design Process

How is this methodology of spacecraft design played out in an industrial setting? The process is very people-intensive, and as such some might observe that it is not quite as objective as you might expect, particularly in the early stages when feasibility and preliminary design issues are addressed. However, we will come back to this perhaps slightly contentious statement later. It is important to set the design method that we have discussed so far in the context of the overall spacecraft development. Spacecraft project activities are traditionally divided into a number of phases, as listed in Table 7.2, taking us from preliminary design through to orbital operations.

Most of what we have said so far falls into phase A, preliminary design, and we do not get much beyond that phase in this book. To get a feeling for how this part of the design is done in a real spacecraft project situation, let's suppose that a company has landed a contract for the phase A study for a particular spacecraft. The process of preliminary spacecraft design that takes place in this phase is sometimes referred to as *spacecraft system engineering*. Definitions of what this means vary, but one possibility is along the lines of "The science of developing an operable spacecraft capable of meeting the mission objectives efficiently, within imposed constraints, such as mass, cost, and schedule." This sounds complicated, but the main job is to design the spacecraft as a collection of subsystems in such a way that, when

Table 7.2 The design and development phases of a spacecraft project

Phase		Duration	Activities
A	Preliminary design and feasibility	6 to 12 months	Creation of a preliminary spacecraft design, and project plan in terms of schedule and cost; the identification of the key technology areas that may threaten feasibility
B	Detailed design	12 to 18 months	Conversion of the preliminary design into a baseline technical solution, including detailed system and subsystem designs; development of a detailed program for subsequent phases
C/D	Development, manufacture, integration, and test	3 to 5 years	Development and manufacture of flight hardware; integration of spacecraft, and extensive ground testing
E	Flight operations	Orbital lifetime	Delivery of spacecraft to launch site; launch campaign; early orbit operations; mission orbit operations; end-of-life disposal from mission orbit

Note: The phase A to D durations are estimates, and vary according to the type of spacecraft.

they are integrated, they produce a total spacecraft design that can efficiently (or even optimally) achieve the objectives of the mission.

Space system engineering is a discipline that differs from spacecraft system engineering. One of the key issues about any kind of system engineering is where you draw the boundary. The focus of this book is concerned with the design of the spacecraft itself (although we do briefly get into launch systems), so we draw a boundary around the spacecraft and focus on it as the system. Space system engineering, on the other hand, draws a wider boundary, not only around the spacecraft but also around all the other parts of the project, such as the ground stations involved in operating the spacecraft and receiving its data. The following discussion does not address these other parts, focusing firmly on the spacecraft.

Returning to the process of spacecraft system engineering, the means of doing this involves forming a design team or committee composed of subsystem engineers, usually with a system engineer as the team leader or chairperson. Each of the spacecraft's subsystems is represented by one or more engineers who are experts in that particular part of the spacecraft. The team leader does not have the same depth of knowledge in any particular subsystem as the team members, but as a system engineer he or she has a breadth of knowledge across the whole system to help in the integration of the overall design.

The traditional method of progressing the design involves lots of off-line analysis and design work by the subsystem engineers, punctuated by numerous meetings of the design team, in which results are discussed and designs are progressed and integrated (it seems odd to be talking about "traditional" methods in spacecraft design, but it is justified by the fact that the space age is half a century old now). This latter aspect is very important. Clearly, each subsystem specialist could work in isolation to produce the most wonderful design solution for his or her own particular corner of the spacecraft. But if it does not integrate with everyone else's subsystem designs, then it is effectively useless.

The team members soon realize that this is design by committee, and that compromise is required by everyone to achieve success at the end of the day, in terms of an integrated spacecraft design. My earlier comment about the objectivity of the process is relevant here. Given how people-intensive it is, spacecraft system engineering could be redefined as the science (*and art*) of developing an operable spacecraft. This work can be a bit of an art form at times, as the outcomes are governed by the dynamics of the team and the interaction among its members. The subsystem specialists have to accept that their own designs will be influenced and modified (perhaps not to their liking!) by inputs from other subsystem or payload specialists.

The other important aspect of this design process is that it is *iterative*. The design team will arrive at an initial design for the spacecraft, but the review of the design will point to areas of the design that can be improved upon considerably, or that may be problematic. The design process is then reviewed—iterated—to overcome these issues in a new design. But the new design may have problems too, and so the process continues until it converges in an acceptable final design.

Over the past decade or so, this traditional method has been transformed by the introduction of computer technology into the process. The basic underlying structure of the design team is still there, but now the team is collocated for the duration of the phase A study in a purpose built design studio equipped with computer work stations. It looks like a miniature version of mission control! Figure 7.2 shows a plan view of such a facility at ESTEC (the European Space Agency's technical head quarters in the Netherlands). Each of the workstations is dedicated to the design of a particular spacecraft subsystem, and as such is loaded with appropriate software to allow operators to do whatever analysis they need to do to

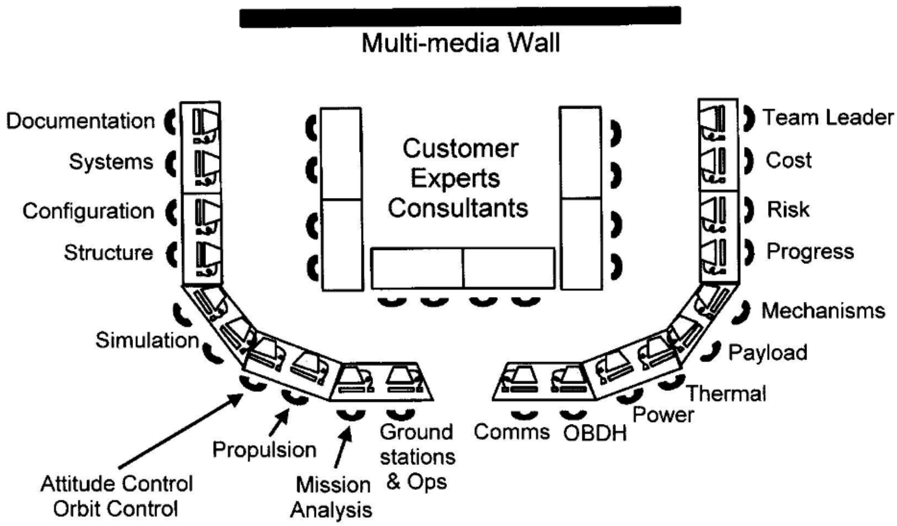

Figure 7.2: A schematic of the computer workstation layout of the European Space Agency's concurrent engineering design facility at ESTEC in the Netherlands. The development of the facility began in 1998. (Backdrop image courtesy of European Space Agency [ESA].)

develop the design. The subsystem engineers comprising the team are now seated at the workstations; for example, the mission analyst sits at the mission analysis workstation, the power engineer at the power workstation, and so on, with the team leader controlling the process from his or her own workstation. The technique is called *concurrent engineering design* (CED), and is being used not just in the space industry but across a broad range of industries involved in the design of complex machines, such as automobiles and airplanes.

At the heart of the process is a central computer database that holds the current design of the spacecraft in memory. Every time team members update the design of their subsystem, the update is relayed to the central database. The details of this change are then available immediately to the other team members, and the impact of the change on the design of the other subsystems can be assessed quickly. The main benefits of this technique are the speeding-up of the process of design iteration that we mentioned above, and an improvement in the process of design integration. The use of CED has typically shortened the time it takes to perform a phase A study of a spacecraft from 6 months or more to 1 or 2 months. However, the introduction of computers into the process has *not* replaced the need for excellent subsystem engineers as design team members. They are still vital in the CED facility to check that the computer output makes sense, and to guide the process to a successful conclusion.

Spacecraft Engineering: The Final Frontier?

Most people, I believe, consider spacecraft engineering to be at the cutting edge of technology, so it comes as something of a surprise that it is often very conservative in its approach. On the one hand, we have subsystem engineers who are always striving to develop new ideas and technologies in their specialist area, to improve the performance of the spacecraft, while at the same time reducing its mass and power requirements. This kind of innovative engineering is the life-blood of the sort of person who becomes a talented and dedicated subsystem specialist. On the other hand, new ideas bring with them questions about their feasibility: Will they work in orbit? How long will it take and how much will it cost to test a new idea to answer these questions to the satisfaction of the project managers? Essentially such innovations introduce risk into the situation, and this kind of risk poses a threat to program schedules, with consequent impact on project costs. Thus we end up in a situation where design solutions that have flown a hundred times before are good, and are automatically adopted in spacecraft designs. This kind of philosophy is common in the design of commercial spacecraft, such as communications satellites. The competition for business among commercial companies in designing and manufacturing these satellites is very stiff, and a particular contractor will invariably adopt conservative engineering solutions in order to minimize cost and schedule in their bid to win the contract. In such situations the time scales for the development phases shown in Table 7.2 are considerably reduced. It is a tough business to be in!

How does the technology progress in spacecraft engineering? It is often the case that innovative engineering is required to build payload instruments for science spacecraft, in order that the boundaries of what has been achieved before can be stretched. However, even on such satellites, the technologies used in the subsystem design—in the spacecraft platform—may be decades old. This is not meant to be a criticism, but may indeed be of benefit in improving the overall reliability of the spacecraft system.

An increasingly popular way of flight-testing new subsystem technologies is through the use of small satellites. There is debate about what is meant by the word "small" in this context, but for our purposes let's think about satellites on the order 50 kg or less. At this sort of mass, and with the continuing trend of miniaturization of computer processors, relatively complex and capable small satellites can be built as flight demonstrators for new technologies. The key to this development is their relatively low cost. In the launch business, satellite mass generally equates to launch costs. Since a small satellite can hitch a ride on a launch vehicle as a minor partner, the cost of launch is hugely decreased. Other factors contributing to their low cost are a short design, build, and test period, and a less complex ground system and operations. Given this low financial risk environment, the consequences of a failure in testing new technologies in orbit are significantly reduced, making the proposition more attractive.

Examples of Current Spacecraft

We conclude this chapter with some examples of current unmanned spacecraft and their applications areas. The main features and subsystem areas (see Table 7.1) of these satellites are shown in figures and described in tables. To put the mass of these spacecraft into perspective, it is helpful to bear in mind that 1000 kg is a metric tonne; a typical automobile weighs about 1¼ to 1½ metric tonnes, and a double-decker bus weighs about 10 metric tonnes. Because the life span of these spacecraft is short, the ones cited here will be relegated to history in a few years. But this book would be incomplete without giving the reader an idea of the mass, size, and appearance of currently flying spacecraft. The particular satellites chosen to represent the different application areas are as follows:

- Communications: Intelsat 8 (Fig. 7.3 and Table 7.3)
- Remote sensing: SPOT 5 (Fig. 7.4 and Table 7.4)
- Science
  - Observatory: Hubble Space Telescope (Fig. 7.5 and Table 7.5)
  - Interplanetary exploration (Cassini/Huygens; Fig. 7.6 and Table 7.6)

Figure 7.3: Artist's impression of the Intelsat 8A communications satellite in geostationary Earth orbit. (Image courtesy of Lockheed Martin.)

Table 7.3: The main features of the Intelsat 8 spacecraft

Description:	Intelsat 8 spacecraft is a typical geostationary Earth orbit (GEO) communication satellite, providing predominantly an intercontinental telephone communication service.
Launch mass:	3250 kg
Dry mass (without fuel):	1540 kg
% of launch mass:	47%
Fuel mass:	1710 kg
% of launch mass:	53%
Approximate size:	Central body is a box 2.2 × 2.5 × 3.2 m
Orbit type:	GEO
Height:	35,790 km
Inclination:	0 degrees
Power (beginning of life):	4.8 kW
Payload	
Mass:	460 kg (estimated)
Mass (% of dry mass):	30% (estimated)
Performance:	The communications payload can carry typically 22,000 telephone calls and 3 color TV broadcasts simultaneously

Figure 7.4: Artist's impression of the SPOT 5 Earth observation satellite in a near-polar low Earth orbit. (© CNES/ Artist David Ducros.)

Table 7.4: The main features of the SPOT 5 spacecraft

Description:	The SPOT series of spacecraft was developed as a French national space program. The spacecraft were designed and manufactured by the French space agency CNES (Centre National d'Étude Spatiales).
Launch mass:	2760 kg
Dry mass (without fuel):	2600 kg
% of launch mass:	94%
Fuel mass:	160 kg
% of launch mass:	6%
Approximate size:	2 × 2 × 5.6 m
Orbit type:	Near polar LEO
Height:	822 km
Inclination:	98.7 degrees
Power (beginning of life):	2.5 kW
Payload	
Mass:	1400 kg
Mass (% of dry mass):	54%
Performance:	Provides images of the ground that are 120 km across, with a resolution of 10 m

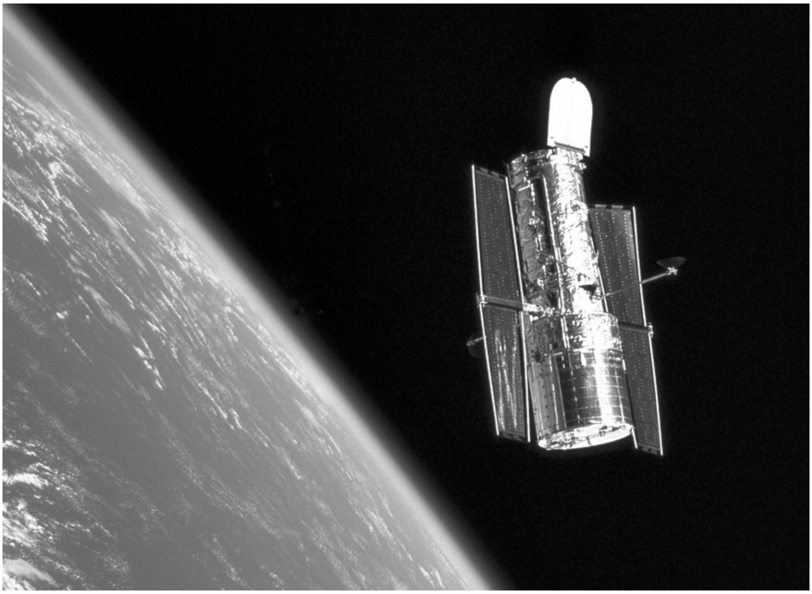

Figure 7.5: Photograph taken by shuttle astronauts of the Hubble Space Telescope in a near-equatorial low Earth orbit. (Image courtesy of National Aeronautics and Space Administration [NASA].)

Table 7.5: The main features of the Hubble Space Telescope

Description:	Named after Edwin Hubble, who discovered the expansion of the universe in the 1920s, this orbiting telescope has revolutionized all aspects of observational astronomy.
Launch mass:	10,840 kg
Dry mass (without fuel):	10,840 kg
% of launch mass:	100%
Fuel mass:	0 kg
% of launch mass:	0%
Approximate size:	A cylinder 13 m long × 4.3 m diameter
Orbit type:	Low inclination LEO
Height:	Approximately 600 km
Inclination:	28.5 degrees
Power (beginning of life):	5 kW
Payload	
Mass:	1450 kg
Mass (% of dry mass):	13%
Performance:	The main element of the telescope is a mirror 2.4 m in diameter that can see objects just 120 m across on the moon's surface

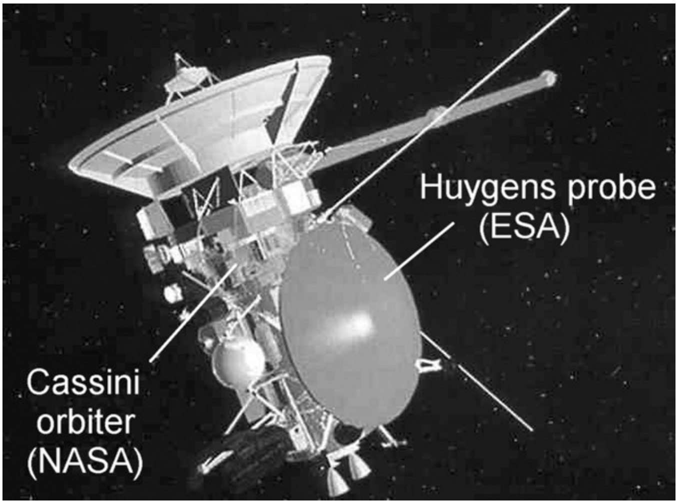

Figure 7.6: The Cassini/Huygens spacecraft configuration. The spacecraft entered orbit around the planet Saturn in July 2004. (Artist's impression by David Seal. Backdrop image courtesy of NASA/Jet Propulsion Laboratory [JPL]—Caltech.)

Table 7.6: The main features of the Cassini/Huygens spacecraft

Description:	The spacecraft is made up of two main parts: Cassini, which is the Saturn orbiter built by NASA, and the Huygens probe built be the European Space Agency (ESA). The Huygens probe successfully landed on Saturn's moon Titan in January 2005.
Launch mass:	5630 kg
Dry mass (without fuel):	2490 kg [2150 kg (orbiter) + 340 kg (probe)]
% of launch mass:	44%
Fuel mass:	3140 kg
% of launch mass:	56%
Approximate size:	6.8 m high, with a 4-m communications dish
Orbit type:	Saturn orbit
Height:	Orbit height continuously modified using swing-bys around Saturn's moons
Inclination:	Near-equatorial
Power (beginning of life):	815 W (using RTGs; see power section in Chapter 9)
Payload	
Mass:	670 kg [330 kg (orbiter payload) + 340 kg (probe)]
Mass (% of orbiter dry mass):	31%
Performance:	The images of Saturn and its moons have been particularly spectacular!