Appendix C

Rendezvous vehicles of the ISS scenario

The objective of this appendix is to provide an overview of the vehicles which perform rendezvous and capture in the ISS scenario. Of interest are the features of these vehicles which are most important for the implementation of the rendezvous trajectories and for the mating process. These are:

- masses and inertias of the vehicles;
- actuation means and force/torque capabilities;
- location of thrust engines;
- features of the vehicle geometry related to rendezvous and capture issues, such as size and shape of main body and appendages;
- type and location of mating devices;
- type of rendezvous sensors;

It is not the intention to give here a detailed and exhaustive description of all these vehicles, which may anyway undergo changes in the course of their development.

General information on the various vehicles can be obtained from the NASA, NASDA and ESA web-sites. Detailed information on design and history of the Russian vehicles can be obtained from NASAs 'Mir hardware heritage' (Portree 1995). Information on all aspects of space stations can be found in Messerschmid & Bertrand (1999). Some information contained in this appendix has been extracted from technical reports and specifications of the International Space Station Programme for the Station and its visiting vehicles (NASA 1999), and some has been obtained by verbal communication from specialists involved in the development of the various spacecraft.

In the first two sections of this appendix, the target vehicles ISS and Mir are discussed, in the following sections the chaser vehicles of the ISS scenario are considered.

C.1 International Space Station

At the time of writing, the International Space Station is the target vehicle for the majority of all rendezvous and docking/berthing operations. In the 'assembly complete' state, the ISS will be the largest spacecraft ever built and for its assembly in orbit more than 20 launches will be necessary. Some of the modules are self-navigating, arriving at, and docking to, the station automatically, whereas other modules and assemblies are delivered to the station by the Space Shuttle. The first module of the ISS, the FGB, was launched in November 1998. Figure C.1 shows the 'assembly-complete' configuration, which, at the time of writing, was planed for 2004.

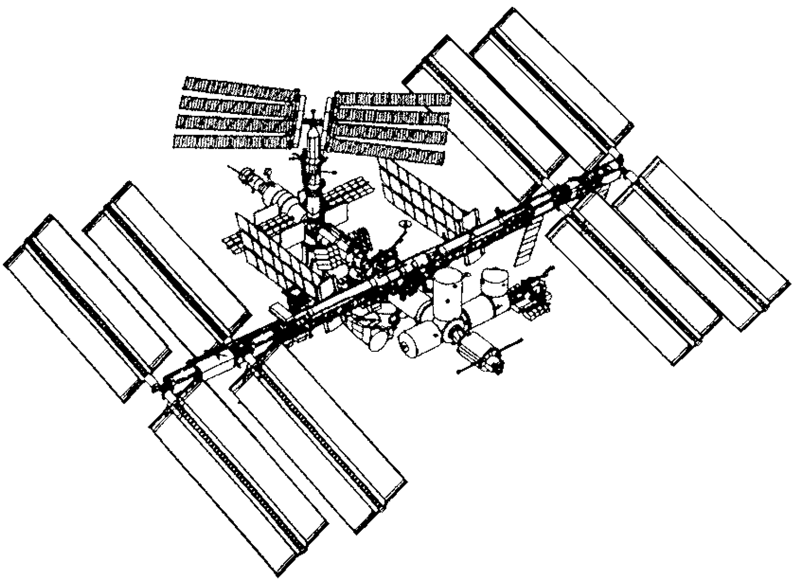

Figure C.1. International Space Station ISS (courtesy NASA).

Design features

The elements of the ISS the 'assembly-complete' configuration are shown in figure C.2 (obtained from NASA (1998c)). In this configuration the ISS will include the following major modules:

- Russian built FGB (the first module of the ISS in orbit);

- Russian Service Module (SM);
- Node 1 (with mating adapters for connection to FGB and for connection of other modules);
- US HAB module (pointing down with the docking port in the R-bar direction);
- US LAB module (in a longitudinal direction);
- Node 2 (pointing with the docking port in V-bar direction);
- Japanese Experiment Module (JEM) (on right side, when looking in flight direction);
- European Laboratory (on left side, when looking in flight direction);
- Centrifuge Module (pointing up);
- Italian Mini Pressurised Module (MPLM) pointing down (this module is not permanently attached, but is transported up and down by the Shuttle);
- Russian Science Power Platform (SPP) (attached to the inter-connecting element of the Service Module);
- second FGB with interconnecting element (attached to the interconnecting element of the Service Module);
- several Russian Research-, Docking- and Storage Modules attached at various places on the Russian side of the ISS.

The dimensions, mass and inertia of the ISS depend on the assembly status and on the number and type of servicing vehicles/modules attached to it. The values given in table C.1 refer to the 'assembly-complete' status, without other vehicles attached. They are estimates, based on the design status before the year 2001.

Orbit parameters

- altitude: 350–460 km;
- inclination: 51.6 deg.

Location and type of docking/berthing ports

The ISS has several ports facilitating the attachment of vehicles and modules. The main type of mating is docking, but due to its manipulator system the ISS has also the capability to attach vehicles or modules by berthing. Berthing techniques will be used, e.g., for the mating of the HTV and for unloading of the payload from the cargo bay of the Space Shuttle Orbiter. The following ports are available:

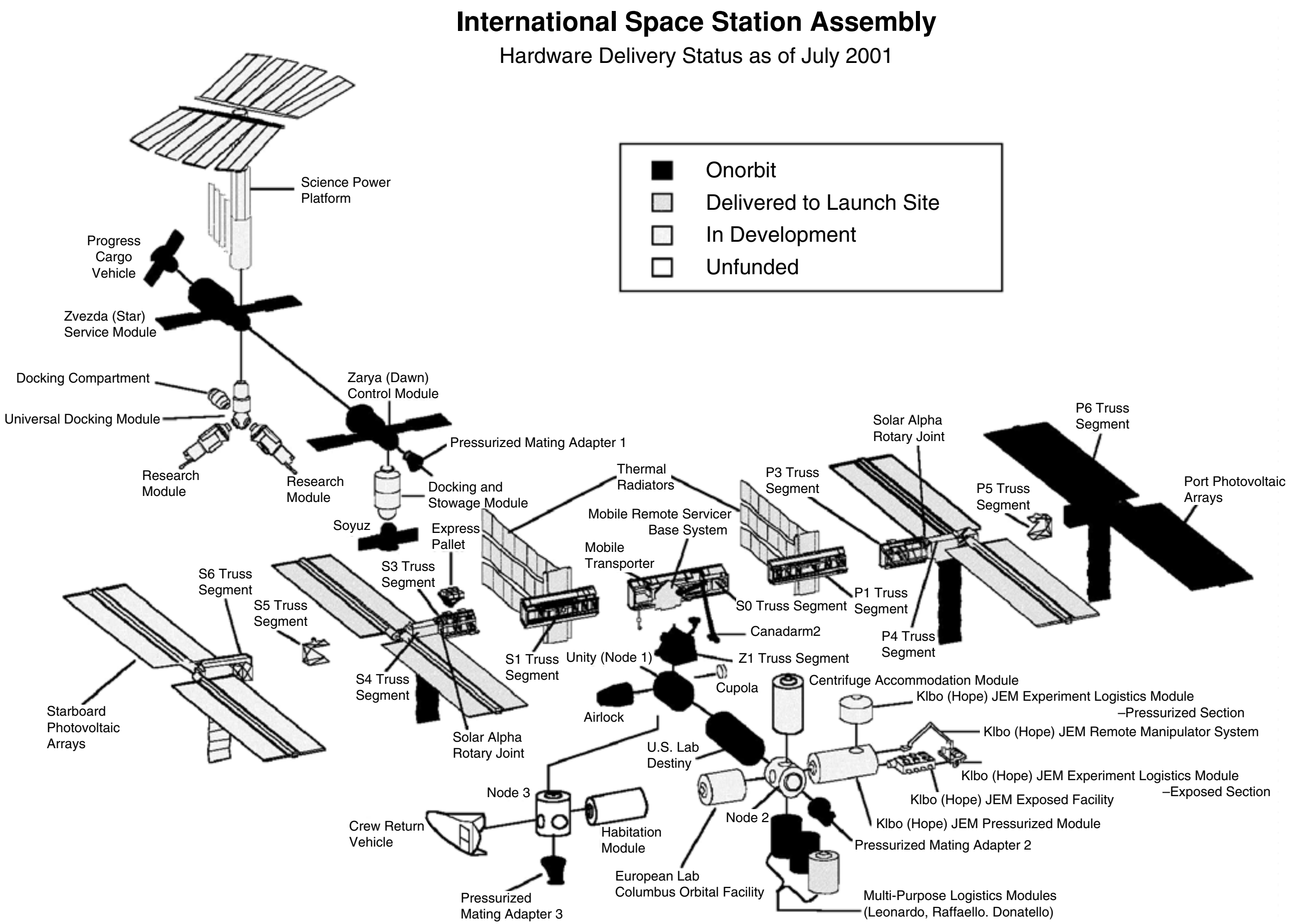

Figure C.2. Modules of the International Space Station, ISS (courtesy NASA).

(1) +V-bar port for docking of the Space Shuttle Orbiter in front of Node 1, APDS-type docking mechanism (see figure 8.10);

(2) R-bar port for docking of the Space Shuttle Orbiter below the US HAB Module, APDS-type docking mechanism (see figure 8.10);

(3) R-bar berthing port for MPLM and HTV at the nadir pointing side of Node 1, CBM type of berthing mechanism (see figure 8.13);

(4) −V-bar docking port for Soyuz, Progress and ATV vehicles aft of the Service Module, probe/drogue type docking mechanism (see figure 8.8);

(5) R-bar docking port for Soyuz and Progress vehicles on the nadir pointing side of the second FGB, probe/drogue type docking mechanism (see figure 8.8);

(6) R-bar docking port for Soyuz and Progress vehicles on the nadir pointing side of the Docking and Storage Module, probe/drogue type docking mechanism (see figure 8.8).

The main ports for visiting vehicles are the +V-bar and −V-bar docking ports at the forward and aft ends of the Station and the R-bar berthing port on Node 1.

Visiting vehicles

It is planned that the ISS will be serviced by the following vehicles:

- the US Space Shuttle (crew and cargo);
- the Russian Soyuz (crew);
- the Russian Progress (cargo, refuelling and re-boost);
- the European ATV (cargo and re-boost);
- the Japanese HTV (cargo).

Additionally there may be a re-boost module delivered by the Space Shuttle for orbit maintenance of the Station.

Rendezvous sensor systems used

The interfaces of the rendezvous sensors of the visiting vehicles and the corresponding functions on the target station are not standardised on the ISS, but are specific to each of the visiting vehicles. For vehicles using optical rendezvous sensors, their according interfaces formed by reflector arrangements are accommodated near to the docking port or berthing box specific for this vehicle. The equipment on the Space Station (transponder) for the Russian Kurs system has been described in section 7.2.5. For RGPS, raw data will be used from one of the GPS receivers on the Station. The sensor systems used are identified below in the sections on the visiting vehicles.

Table C.1. Dimensions, mass and moments of inertia of ISS.

Dimensions	$x = 67.5$ m $y = 108.48$ m $z = 44.98$ m rotational envelope of solar arrays $d = 72.93$ m
Mass	$m = 470\,000$ kg, depending on payload
Principal moments of inertia	$I_{xx} \approx 128\,000\,000$ kg m^2 $I_{yy} \approx 107\,000\,000$ kg m^2 $I_{zz} \approx 201\,000\,000$ kg m^2

Actuators

Rotating actuators Four control moment gyroscopes (CMGs) with a two DOF gimbal system, providing a maximum torque of about 250 N m. The CMGs are mounted on the truss. Attitude control will be performed mainly by control moment gyros.

Thrusters RCS thrust engines will be used, mainly for CMG de-saturation, but also for slew manoeuvres and for control of position. For pitch and yaw control the thrust engines of the Service Module will be used, if no visiting supply vehicle (Progress, ATV) is attached to its docking port. It is a requirement of the ISS that visiting vehicles docked to the Service Module will provide thrust support for attitude control. For roll control, to provide sufficient lever arm, thrusters attached to the Science Power Platform (SPP) were planned. In the case of a configuration of the Station without the SPP, the thrusters of a vehicle (e.g. Soyuz or Progress), attached to the inter-connecting element of the second FGB, could be used.

Re-boost manoeuvres for orbit maintenance will be performed mainly by visiting vehicles, i.e. Progress and ATV, and possibly by the above-mentioned re-boost module. If no visiting vehicle is attached, the main thrusters of the Service Module can be used for re-boost of the Station.

The thrust levels (of thrusters on the Service Module) are as follows:

- 32 bi-propellant attitude control thrusters, thrust level: 130 N;
- two re-boost thrusters, thrust level: 3070 N;

The locations of the thrusters on the Service Module are as follows:

- attitude control thrusters: in four groups on the cylindrical surface at the aft of the SM;

- re-boost thrusters on the aft plane of the SM.

The thrusters of the visiting vehicles used for attitude control and re-boost are addressed in the respective sections below.

C.2 Russian Space Station 'Mir'

The Russian space station Mir played a significant role in the preparation phase of the International Space Station Programme. A large number of international crew members obtained operational experience aboard the Mir station. The US Space Shuttle visited Mir ten times within the context of this preparation programme. During the first visit the Shuttle performed rendezvous only down to a distance of 12.2 m without docking. Mir is described here as a second reference example of a target station in the rendezvous process because it has been involved in the largest number of rendezvous and docking operations of all spacecraft so far, and will be used as reference in many years to come. Mir was de-orbited on 23 March 2001.

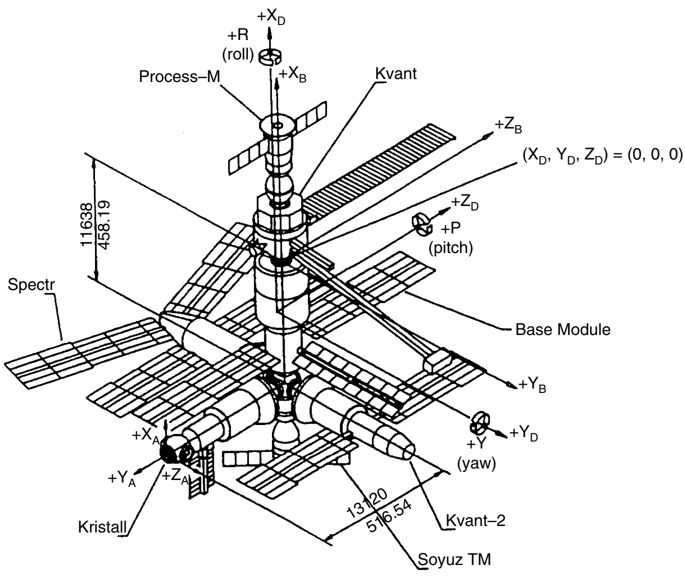

Figure C.3. Russian space station Mir (courtesy RSC Energia).

Design features

The first module of Mir, the Base Block, was launched in 1986. The Base Block had an aft docking port and an inter-connecting element with five ports at its forward end. The size of the station was increased and its configuration was modified by adding further modules:

- the Kvant Module in 1987;
- the Kvant-2 Module in 1989;
- the Kristall Module in 1990;
- the Spektr Module in 1995;
- the Docking Module for Space Shuttle dockings in 1995;
- the last addition, the Priroda Module in 1996.

The first Kvant was attached to the aft port of the Base Block; the other modules, except for the Docking Module, were attached to the inter-connecting element of the Base Block. The Docking Module was attached to the Kristall Module. A manipulator arm was available to re-configure the station by moving a module to a different port. The mating process used for all vehicles with Mir was docking.

The dimensions, mass and moments of inertia of Mir were dependent on the configuration and were therefore increasing with the attachment of each new module. Typical values for the configuration prior to attachment of the Priroda Module are shown in table C.2.

Table C.2. Dimensions, mass and moments of inertia of Mir.

Dimensions	$x = 33.14$ m (Base Block and Kvant plus one Soyuz and one Progress vehicle attached) $y = 27.35$ m (body length of Kvant 2 + inter-connecting element + Spektr) $z = 29.67$ m (span of solar arrays of Base Block)
Mass	$m = 111\,600$ kg
Principal moments of inertia	$I_{xx} \approx 3\,600\,000$ kg m^2 $I_{yy} \approx 7\,000\,000$ kg m^2 $I_{zz} \approx 8\,100\,000$ kg m^2

Module properties

- Base Block: mass 20.4 ton, length 13.13 m, max. diameter 4.15 m;
- Kvant: mass 11.5 ton, length 5.8 m, max. diameter 4.15 m;
- Kvant-2: mass 19.6 ton, length 13.73 m, diameter 4.35 m;

- Kristall: mass 19.64 ton, length 13.73 m, diameter 4.35 m (including inter-connecting element with two APAS docking ports);
- Spektr: mass 19.5 ton, length 12 m, diameter 4.4 m;
- Priroda: mass 19 ton, length 13 m, diameter 4.3 m.

The configuration shown in figure C.3 is the one prior to arrival of the Spektr Module in 1995.

Orbit parameters

- altitude: 330–390 km;
- inclination: 51.6 deg.

Location and type of docking ports

- Two probe/drogue type docking mechanisms (see figure 8.8) along the x-axis of the complex, on the aft of the Kvant module and on the opposite side on the inter-connecting element of the base block.
- Two APDS-type docking mechanisms (see figure 8.10) on the inter-connecting element of the Kristall module and on the docking module for the Space Shuttle, which was attached to one of the APDS ports of Kristall in 1995.

Visiting vehicles

Mir was serviced/visited by

- the Russian Soyuz (crew);
- the Russian Progress (cargo, re-fuelling and re-boost);
- the US Space Shuttle (crew and cargo).

Rendezvous sensor systems

In the first years of the Mir station the older IGLA system (also an RF-sensor system) was used. The Kurs system was installed in 1989 (see section 7.2.5).

Actuators

Rotating actuators

- Up to 12 control moment gyros (called 'gyrodynes'), located in the various modules.

Thrusters The thrust levels were:

- Base Block, Kvant, Progress: 135 N;
- Kvant2, Spektr: 390 N.

The thruster locations were as follows:

- Each of the Mir modules had its own set of thrusters. Additionally the thrusters of the attached Progress vehicle were used for attitude and trajectory control and for orbit maintenance.

C.3 Space Shuttle Orbiter

Mission objectives

The US Space Shuttle is the largest transport vehicle in the ISS scenario. It can transport up to seven crew and of the order of 15 000 kg of payload to the ISS orbit (depending on station altitude and payload geometry). With its 60 ft long and 15 ft diameter payload bay (the space necessary for the docking mechanism and its substructure has to deducted), the Space Shuttle is capable of transporting the largest Modules to the ISS.

Design features

Body features of the Space Shuttle Orbiter in terms of dimensions, mass and moments of inertia are indicated in table C.3.

Table C.3. Dimensions, mass and moments of inertia of the Shuttle Orbiter.

Dimensions	$x = 37.24$ m (12.17 ft)
	$y = 23.79$ m (78.06 ft)
	$z = 17.25$ m (56.58 ft)
Mass[a]	$m = 90\,700$–$104\,330$ kg (200 000–230 000 lb)
Principal moments	$I_{xx} \approx 1\,310\,000$ kg m^2
of inertia[b]	$I_{yy} \approx 10\,220\,000$ kg m^2
	$I_{zz} \approx 10\,650\,000$ kg m^2

[a] At landing, depending on mission. The rendezvous mass will be nearer to the larger value.
[b] Typical values, depending on mission and payload.

Launcher

The Space Shuttle is an integrated launch system using solid fuel strap-on engines plus an external liquid fuel tank and the main engines of the Orbiter for the launch boost.

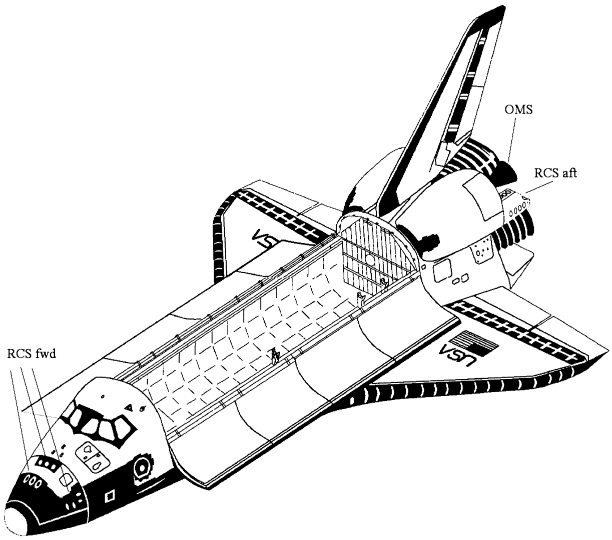

Figure C.4. Space Shuttle Orbiter (courtesy NASA).

Mating system

This is an APDS-type docking mechanism (see figure 8.10) .

The docking system is mounted on a bridge on the forward end of the cargo bay. The Orbiter attaches itself to the Station by docking. The nominal contact velocity is <0.05 m/s. The payload is transferred and attached to the Station by a manipulator in a berthing type of process.

Rendezvous sensor systems

These comprice star tracker, rendezvous radar, Crew Alignment Sight (COAS) and Trajectory Control Sensor (TCS) (see section B.1 and figure B.2).

Thrusters

(a) Orbital Maneuvering system (OMS): two bi-propellant rocket engines for major orbit changes.

(b) Reaction control system (RCS): 44 bi-propellant engines for attitude- and trajectory control.

Thrust level

(a) Orbital manoeuvring system (OMS): 26 700 N (6000 lb) each.

(b) Reaction control system (RCS): 3871 N (870 lb) primary engines; 107 N (24 lb) vernier engines.

Location

(a) Orbital manoeuvring system (OMS): on both sides at the base of the vertical tail.

(b) Reaction control system (RCS):

- two aft RCS groups, one at each side of the aft fuselage pod near the OMS engines: there are 12 primary and two vernier engines in each group;
- forward RCS group: 14 primary and two vernier on both sides and on top of the Orbiter nose.

C.4 Soyuz

The Russian Soyuz vehicle has a long design heritage: the original concept dates from 1963, the first flight of an unmanned Soyuz vehicle took place in 1966, and the first manned mission was in 1967. The design of the vehicle has been improved over the years and has been adapted according to the needs of the particular mission scenario, i.e. the various Salyut space stations, the Apollo–Soyuz Test Program (ASTP), Mir and eventually the ISS. The data given below are valid for the Soyuz–TM configuration, which has been in use since the emergence of the Mir Station.

Detailed information on the design and history of Soyuz can be obtained from NASA web sites and from Portree (1995).

Design features

The vehicle is composed of three modules: the Orbital Module, the Descent Module and the Service Module. The first carries the crew to the target station and has a docking mechanism located at its front end. The second is the re-entry vehicle for return to ground. The last third of the Soyuz vehicle is formed by the so-called Instrument Service Module, which contains all functions necessary for the operation of the spacecraft, i.e. propulsion, avionics, communications, power and thermal control functions. The physical properties of Soyuz in terms of dimensions, mass and moments of inertia are shown in table C.4.

Table C.4. Dimensions, mass and moments of inertia of Soyuz-TM.

Dimensions	length = 7.5 m
	diameter = 2.7 m (without appendages)
	solar arrays: span 10.6 m, area 10 m^2
Mass	$m \approx 6850$ kg at mating
	CoM location ≈ 3.8 m from docking plane
Principal moments	$I_{xx} \approx 5300$ kg m^2
of inertia[a]	$I_{yy} \approx 33000$ kg m^2
	$I_{zz} \approx 33000$ kg m^2

[a] Depending on payload.

Mission objectives

- Transfer of up to three crew to and from the target space station.
- Transfer of a small amount of payload to the target station (200–250 kg) and back to ground (70–90 kg).

Launcher

The Soyuz spacecraft is launched by the Russian Soyuz launcher.

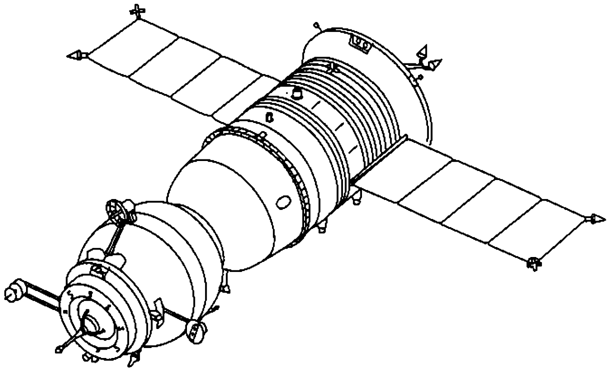

Figure C.5. Soyuz crew transport vehicle (development RSC Energia).

Mating system

A probe/drogue type docking mechanism (see figure 8.8) is mounted on the forward end of the vehicle. The acceptable range of contact velocities is 0.1–0.35 m/s.

Rendezvous sensor system

The Kurs sensor system (see section 7.2.5) is used.

Thrusters

Thrust level

- 1×3000 N main engine;
- 14×130 N translation control;
- 12×26 N attitude control;

Location The main engine is located in the centre of the aft plane, the force is in the $+x$-direction. The trajectory and attitude control engines are located at the rim of the aft plane and on a ring at the interface between the Service Module and the Descent Module.

C.5 Progress

The Russian Progress vehicle has been developed as an unmanned cargo carrying version of Soyuz, and its first flight took place in 1975. Progress was built primarily for the re-supply of the Salyut stations. Its design has continually been updated, according to the needs of the various mission scenarios. The data given below are valid for the Progress-M configuration in use since its first launch in 1989.

Design features

The vehicle is composed, similar to the design of Soyuz, of three modules: the Cargo Module, the Re-fuelling Module and the Service Module. The first carries the pressurised cargo to the target station and has a docking mechanism located at its front end. The second contains propellant tanks for re-fuelling and re-boosting of the station. The third module is, as in the case of the Soyuz vehicle, the so-called Instrument Service Module. It contains all the functions necessary for the operation of the spacecraft, i.e. propulsion, avionics, communications, power and thermal control functions. The body features of Progress in terms of dimensions, mass and moments of inertia are indicated in table C.5.

Table C.5. Dimensions, mass and moments of inertia of Progress.

Dimensions	length = 7.23 m
	diameter = 2.72 m (without appendages)
	solar arrays: span 10.6 m, area 10 m^2
Mass	$m \approx 7130$ kg (at launch)
Principal moments	$I_{xx} \approx 5100$ kg m^2
of inertia[a]	$I_{yy} \approx 31000$ kg m^2
	$I_{zz} \approx 31000$ kg m^2

[a] Depending on payload.

Mission objectives

- Transfer of a maximum of 2600 kg of combined dry, liquid and gaseous cargo to the target space station for logistics re-supply and experiments.
- Transfer of approximately the same amount of waste at re-entry back into the atmosphere for burning up.
- Orbit maintenance of the target station using the main engine.

Launcher

The Progress spacecraft is launched by the Russian Soyuz launcher.

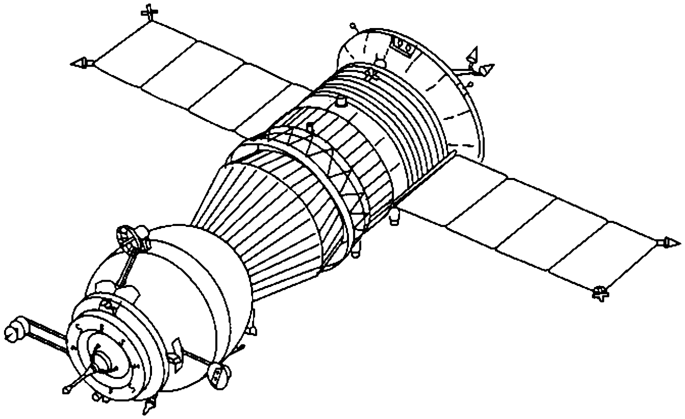

Figure C.6. Progress cargo transport vehicle (development RSC Energia).

Mating system

A probe/drogue type docking mechanism (see figure 8.8) is mounted on the forward end of the vehicle. The acceptable range of contact velocities is 0.1–0.35 m/s.

Rendezvous sensor system

The Kurs sensor system (see section 7.2.5) is used.

Thrusters

Thrust level

- 1×3000 N main engine;
- 28×130 N translation and attitude control.

Location The main engine is located in the centre of the aft plane, the force is in the $+x$-direction. The trajectory and attitude control engines are located at the outer diameter of the aft plane and on a ring at the interface between the Service Module and the Descent Module.

C.6 ATV

Design features

The European ATV is developed specifically for the ISS scenario. The vehicle consists of two modules: a Spacecraft Function Module and a Payload Carrier. The vehicle has a payload carrying capability into the ISS orbit of up to 6900 kg including propellant for re-boost of the Station. The dimensions, ranges of mass and moments of inertia of the ATV are indicated in table C.6.

Mission objectives

- To transport to the ISS dry pressurised cargo for crew supply, experiments and logistics.
- To transport to the ISS water and gases.
- To re-fuel the ISS with fuel and oxidiser.
- To provide propellant for re-boost of the Station to a higher orbit.
- To remove waste for burning up at re-entry.

Table C.6. Dimensions, mass and moments of inertia of the ATV.

Dimensions	length = 9.03 m diameter = 4.48 m (without appendages) solar arrays: span 22.28 m, area 4×8.4 m^2
Mass[ab]	$m \approx 13\,000$–$19\,600$ kg at docking
Principal moments of inertia[a]	$I_{xx} \approx 41\,000$–$59\,000$ kg m^2 $I_{yy} \approx 82\,000$–$138\,000$ kg m^2 $I_{zz} \approx 82\,000$–$138\,000$ kg m^2

[a] Values at docking depend on the payload.
[b] COM location: 2.5–4.25 m from origin of reference system at Ariane interface plane

Launcher

The ATV is launched by the European Ariane V launcher.

Mating system

A Russian probe/drogue type docking mechanism (see figure 8.8). is used. The ATV will dock to the $-$V-bar port on the Service Module of the ISS. The nominal contact velocity is 0.05–0.10 m/s.

Rendezvous sensors

- $>$30 km: absolute GPS;
- 30 km–500 m: RGPS (see section 7.3.3);
- $<$500 m: scanning laser range finder type of optical sensor (see section 7.4.1);
- $<$20 m: camera type of optical sensor (see section 7.4.2).

Thrusters

There are four main engines and 28 RCS engines.

Thrust level

- Main engines 490 N;
- RCS thrusters 220 N.

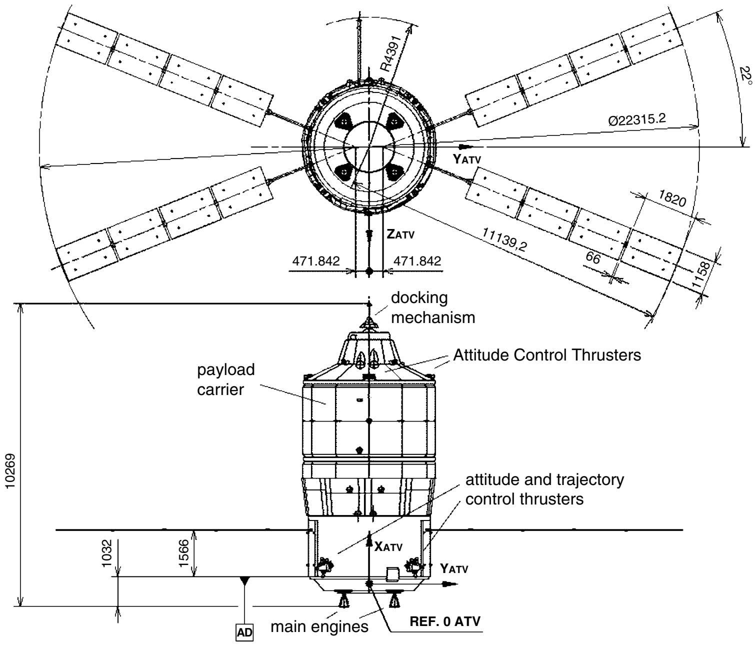

Figure C.7. Automated Transfer Vehicle ATV (courtesy ESA).

Location

- The main engines are at the aft plane of the ATV.
- The RCS engines in four groups of five thrusters each on the Propulsion Module at the aft of the vehicle and four groups of two thrusters each at the forward end of the cylindrical part of the payload carrier.

C.7 HTV

Design features

The Japanese HTV is also specifically developed for the ISS scenario. The spacecraft consists of three modules: a Propulsion Module, an Avionics Module and a Logistics Carrier (see figure C.8). The Logistics Carrier comes in two versions: a pressurised carrier and a mixed carrier with a section for pressurised cargo and an unpressurised section. Figure C.8 shows the mixed carrier version. The payload carrying capability to the ISS orbit is 6000 kg for the mixed version and 7000 kg for the pressurised version. The HTV has solar panels surrounding its body. It receives its power supply from both solar panels and batteries. Typical values for the body features of the HTV in terms of dimensions, mass and moments of inertia are indicated in table C.7.

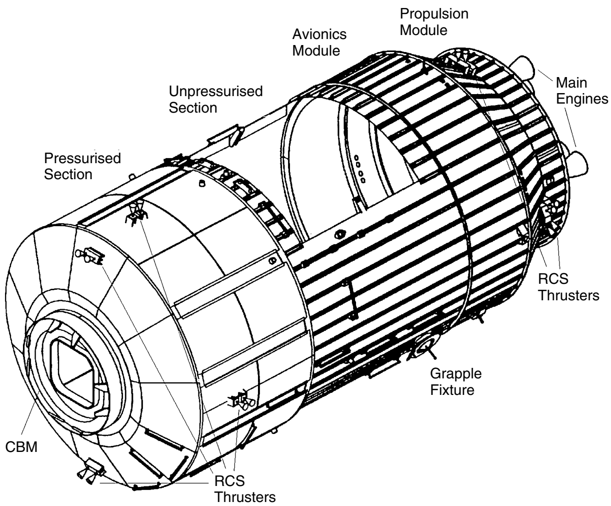

Figure C.8. H-II Transfer Vehicle, HTV (courtesy NASDA).

Mission objectives

- The transportation of experiments and re-supply cargo to the pressurised modules of the ISS.
- The transportation of experiments and equipment for outside accommodation on the ISS (e.g. on ISS Truss, or the platform of the JEM).
- The removal of waste for burning up at re-entry.

Launcher

The HTV is launched by the Japanese H-IIA launcher.

Mating system

- Capture: grapple fixture for manipulator end effector (see figure 8.28). The HTV is captured by the Remote Manipulator System of the ISS in a berthing box below the Japanese Experiment Module. The nominal relative velocity at capture is zero.
- Attachment: CBM type of berthing mechanism (see figure 8.13). The HTV is berthed to the nadir port of Node 2.

Rendezvous sensors

- $>$23 km: absolute GPS;

Table C.7. Dimensions, mass and moments of inertia of the HTV.

Dimensions	length = 7.4 m (pressurised logistics carrier), length = 9.2 m (mixed logistics carrier) diameter = 4.4 m
Mass[a]	$m \approx$ 15 ton (launch mass)
Principal moments of inertia[a]	$I_{xx} \approx 41200$ kg m^2 $I_{yy} \approx 128500$ kg m^2 $I_{zz} \approx 128500$ kg m^2

[a] Values depend on the payload.

- 23 km–500 m: RGPS (see section 7.3.3);
- $<$500 m: optical laser range finder type rendezvous sensor (see section 7.4.1).

Thrusters

There are four Main engines and 28 RCS thrusters.

Thrust level

- 500 N main engine;
- 120 N RCS thruster.

Location

- The main engines are at the aft plane of the HTV.
- The RCS engines are in four groups of four around the Propulsion Module, in four groups of two around the forward part of the Payload Carrier, and in two groups of two on the front side of the vehicle.