Appendix B

Rendezvous strategies of existing vehicles

B.1 Space Shuttle Orbiter

The description of the rendezvous strategy of the US Space Shuttle Orbiter is based on information obtained by the author and his colleagues during various meetings with NASA on the rendezvous sensor demonstration missions on the Shuttle flights STS-80, STS-84 and STS-86 to the Mir Space Station (see also section 10.7.2). Additional information has been obtained from NASA documentation on these missions (NASA 1996, NASA 1997) and from corresponding information by RSC Energia. A further source was NASA's *Rendezvous/Proximity Operations Crew Training Handbook* (NASA 1989).

The phasing strategy of the Space Shuttle consists of a number of standard manoeuvres, which aim to achieve a viable phasing orbit, to adjust the orbit plane to that of the target and to arrive at an initial aim point Ti at a fixed distance from the target and at a particular time. The various manoeuvres shown in figure B.1 have the following purposes:

- *OMS2*. Boost manoeuvre executed by the 'Orbital Maneuvering System' to raise the perigee and achieve viable phasing orbit.

- *NC*. Series of in-plane manoeuvres to support phasing, to adjust perigee and correct thrust errors from the previous manoeuvres. NC manoeuvres are usually performed at the end of a crew working period and prior to sleep.

- *NH*. Larger height adjustment manoeuvre. The necessity of such larger in-plane manoeuvres will depend on the launch injection conditions and on the target position.

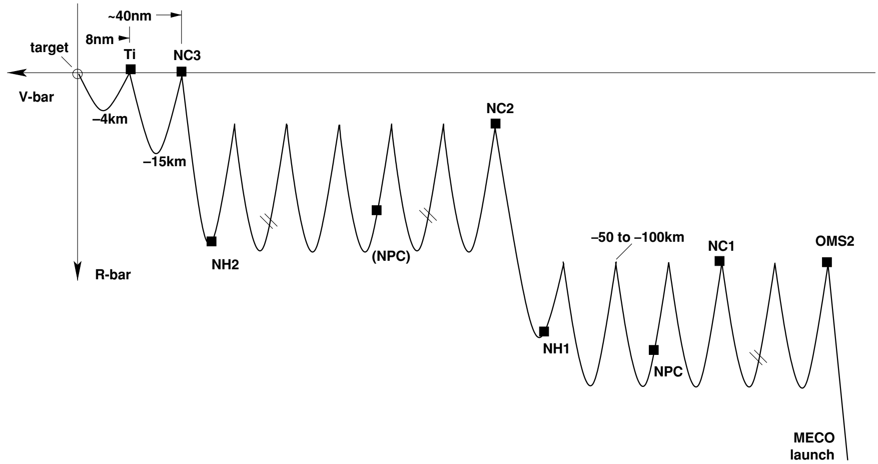

Figure B.1. Example of phasing and far range rendezvous strategy of the Space Shuttle. Note: nm = nautical miles.

- *NPC*. Orbit plane correction manoeuvre. This lateral manoeuvre may be executed at a convenient point of the phasing trajectories to correct RAAN and inclination errors.

All manoeuvres up to the last NC (NC3 in figure B.1) are controlled from ground. The subsequent manoeuvres are controlled autonomously by the onboard GNC system based on star tracker and rendezvous radar measurements. Along the transfer trajectories, the cargo bay of the Shuttle points towards the target. The navigation filter processes all inputs of star tracker, rendezvous radar, inertial measurement unit, thrust commands and the inputs of initial conditions by ground. It propagates the state vector of the vehicle as described in section 6.2.1 above.

- *NCC*. First manoeuvre controlled by the onboard system using filter information updated by star tracker measurements of two previous orbital arcs. The manoeuvre will have in- and out-of-plane components to arrive at Ti in-plane and with the required accuracy.

- *Ti*. Terminal phase initiation manoeuvre. This manoeuvre is executed at a fixed point of 8 nautical miles (14.8 km) behind and 1200 ft (355 m) above the target. All previous manoeuvres are calculated to meet this initial aim point.

- *MC*. Mid-course correction manoeuvre, correcting thrust dispersions of the Ti manoeuvre, measurement errors, residual out-of-plane components, etc., based on Lambert targeting.

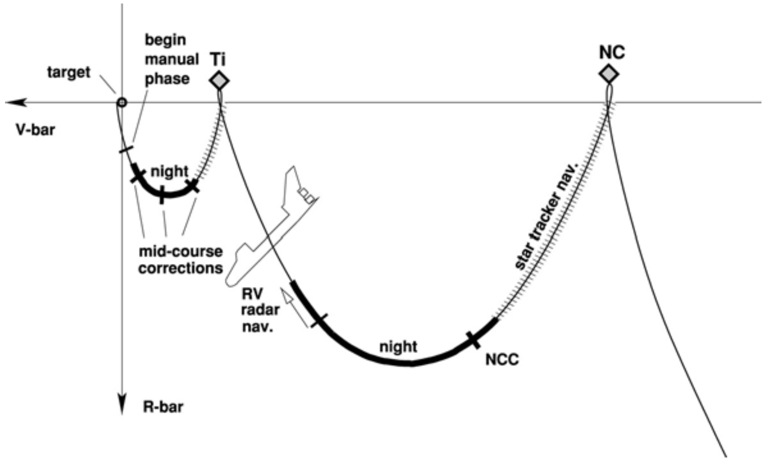

Figure B.2. Typical far range rendezvous profile of the Space Shuttle.

During the last arc, shortly before crossing R-bar, the manually controlled phase commences. Sensors that are available to the crew to increase navigation accuracy, in addition to the rendezvous radar, are:

(1) Crew Optical Alignment Sight (COAS), a passive optical instrument aligned with the *x*-axis of the Orbiter;

(2) Closed Circuit Television System (CCTV), a system of two cameras, mounted at the front and aft ends of the cargo bay, measuring the angle between the *x*-axis and the target;

(3) Trajectory Control Sensor (TCS), a laser range finder type of sensor (see section 7.4.1), capable of measuring range and LOS angles.

Nominal approaches of the Space Shuttle are on the +V-bar and +R-bar sides. Depending on whether a V-bar or R-bar approach is planned, manoeuvres after V-bar crossing will differ.

In a *V-bar approach*, the trajectory is targeted at a point approximately 150 m in front of the target, where a stop pulse is applied. Inside a range of 300 m, the Orbiter has to maintain a velocity profile of range/1000 s. The final approach starts with a velocity toward the target and continues with hops, where a ΔV in the z-direction is applied each time the vehicle crosses V-bar (see figure B.3; see also figure 3.24 for a straight line V-bar approach).

In an *R-bar approach*, an impulse in the $-x$-direction is given at R-bar crossing to reduce the forward velocity. Thereafter, an impulse is applied in the $-z$-direction to compensate for the natural orbital motion, which would have resulted in a $-x$- and $+z$-direction of the trajectory. Each time the vehicle crosses R-bar, a ΔV is applied in

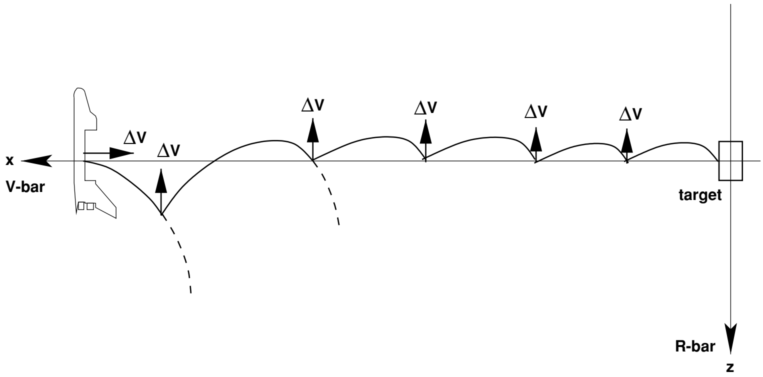

Figure B.3. V-bar approach of the Space Shuttle.

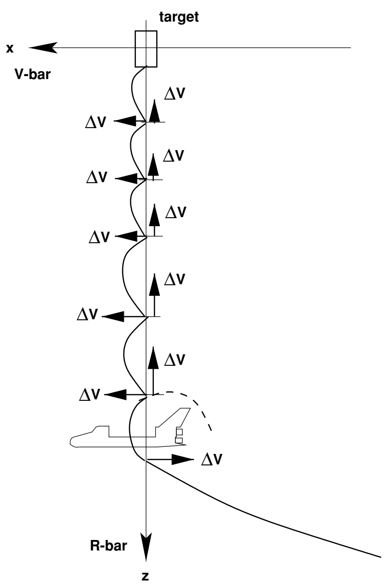

Figure B.4. R-bar approach of the Space Shuttle.

the $-z$-direction, and the vehicle moves in hops along R-bar toward the target (see figure B.4; see also figure 3.25 for a straight line R-bar approach).

A decrease in the approach velocity is achieved in the V-bar approach by reduction in the thrust applied at V-bar crossing (cf. Eq. (3.47) for a straight line approach). In the R-bar approach, the thrusts to be applied are a combination of a ΔV in the $-x$-direction and a ΔV in the $-z$-direction. As shown in figure 3.25, for a constant approach velocity the ΔVs in the $-z$-direction decrease with decreasing altitude difference to the target. The same occurs in an approach where the thrusts occur at discrete points in time instead of continuously. If a velocity profile has to be implemented in an R-bar approach, both ΔV_x and ΔV_z will have to be modified accordingly (cf. Eqs. (3.52) for a straight line approach).

In figure B.2, it is shown that the trajectory crosses R-bar shortly after orbital night. In a V-bar approach, the Orbiter arrives at V-bar approximately at orbital noon. The final approach up to capture will then take place during the second half of the illuminated part of the orbit (see also figure 5.17), with the Sun above and behind the target. In an R-bar approach, the final approach starts directly after R-bar crossing, so that it can take place in the first half of the orbital day. In both cases the Sun will be in front of the approaching vehicle, which may be a disturbance to the pilot. Hold points can be included, on V-bar at any position, and on R-bar at a close distance to the target to save propellant or to wait for more suitable illumination conditions. In the approach from the +R-bar side, the Sun will never illuminate the target docking port side. In this case artificial illumination has to be used for the black and white target pattern used to guide the last part of the approach up to contact.

B.2 Soyuz/Progress

The description of the Soyuz and Progress rendezvous strategy is based mainly on information obtained by the author and his colleagues during various meetings with RSC Energia in the context of the work on ATV. Further sources included a report by the Russian organisation TsNII Mash 1993, prepared in support of the European Hermes project (TsNII-Mash 1992), and a report by CNES 1998 after a meeting with specialists of the Russian mission control centre (TSUP) (Labourdette & Martin 1998).

In contrast to the Space Shuttle, the phasing strategy of the Soyuz and Progress vehicles is based on near circular orbits. This makes the planning of manoeuvres and the time schedule easier. The standard phasing manoeuvres are executed in three sets of one to three boosts (see figure B.5). The strategy takes into account the location and occurrence of communication visibility windows.

(1) The objective of the first set of boosts is to transfer the vehicle to the correct phasing altitude; they are calculated according to the phase angle after launch, according to the altitude of the station, and to the intended time of arrival, to meet proper docking conditions. The manoeuvre set is a Hohmann type transfer, combined

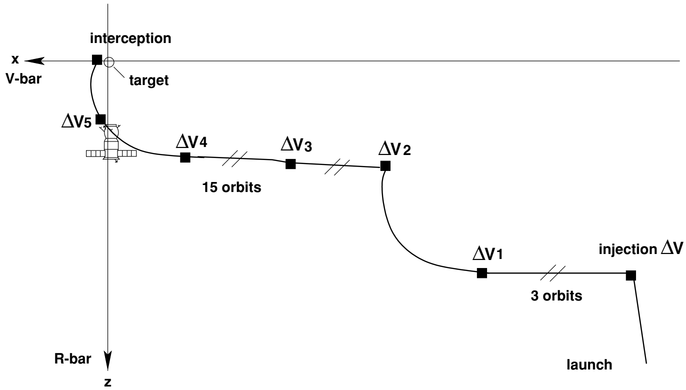

Figure B.5. Phasing strategy of the Soyuz and Progress vehicles.

with orbit plane corrections, and will be executed during the fourth to fifth orbital revolution after launch.

(2) The next manoeuvre will be performed during the 17th orbital revolution. Its purpose is to correct trajectory errors arising after the first set of manoeuvres.

(3) The third set of manoeuvres consists of three boosts, the first two of which, M4 and M5, are calculated to ensure interception of the target orbit precisely at the aim point. The final manoeuvre would inject the chaser vehicle into the target orbit in front of the target, at a distance of approximately 1.5 km. The implementation of this manoeuvre is described in more detail below. The boosts of the third set are performed during the 32nd and 33rd orbital revolutions.

Phasing manoeuvres are executed by the main engines, basically as tangential boosts. Lateral thrust components are obtained by the according attitude angles of the vehicle, e.g. out-of-plane components by yaw angles, in-plane radial components by pitch angles. Whereas the first two sets of manoeuvres are controlled from ground, the last set is implemented automatically by the onboard control system, using, for the calculation of manoeuvres M5 and M6, the measurements of the Kurs rendezvous sensor system (see section 7.2.5). Manoeuvre M4 is calculated and executed by the onboard system based on orbital parameters and conditions loaded into the onboard computer during the previous phase. Preliminary values for manoeuvre M5 and for the injection manoeuvre M6 at the aim point are calculated prior to M4 as a solution to the three-impulse-transfer problem. The preliminary results for $\Delta V6$ obtained in this way are kept as reference by the onboard system.

Shortly after M4, the trajectory enters into the operational range of the Kurs system. The control system will then calculate, based on the relative state vector established by Kurs, an update of the time at which M5 should be executed, an update of the values

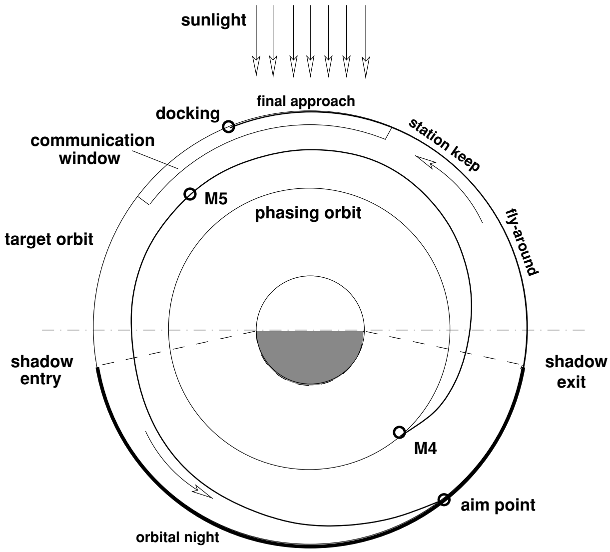

Figure B.6. Rendezvous phase of the Soyuz and Progress vehicles.

of the thrust components of M5 in three directions and of the expected relative velocity at the aim point. To attain a smooth braking velocity profile when arriving at the target orbit, the necessary braking impulse is actually implemented in three manoeuvres (M6–M8), where the first (M6) is applied about 1 km below the target orbit. This first manoeuvre is executed by the main engines, the other two by the attitude control thrusters. Except for the boost with the main engines, the spacecraft points along the approach trajectory toward the target.

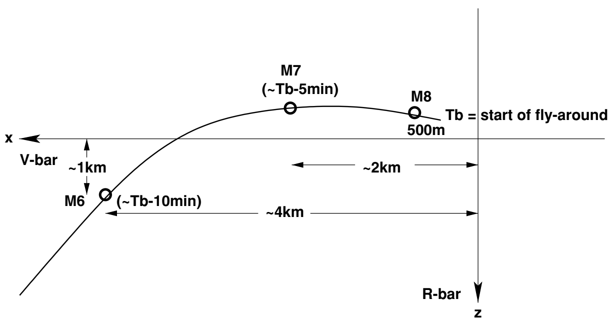

Figure B.7. Soyuz/Progress manoeuvres at V-bar arrival.

An important requirement for the final approach and docking is the illumination of the target docking port. For monitoring reasons, the target should be illuminated by the Sun with an angle between 30 and 60 deg w.r.t. the docking axis (see also section 5.4.1). For this purpose the Sun must be behind the chaser, which is the case for a +V-bar approach in the first half of the orbital day, for a −V-bar approach in the second half and for a −R-bar approach in the two sectors before and after orbital noon. As we have seen in the previous section, there will be no such condition for the +R-bar approach, as the Sun will always be in the hemisphere behind the target. A further constraint which had to be taken into account for the design of the Soyuz/Progress approach strategy, was the fact that the target station (Mir) could have both LVLH and inertial (Sun-pointing) attitude for power reasons.

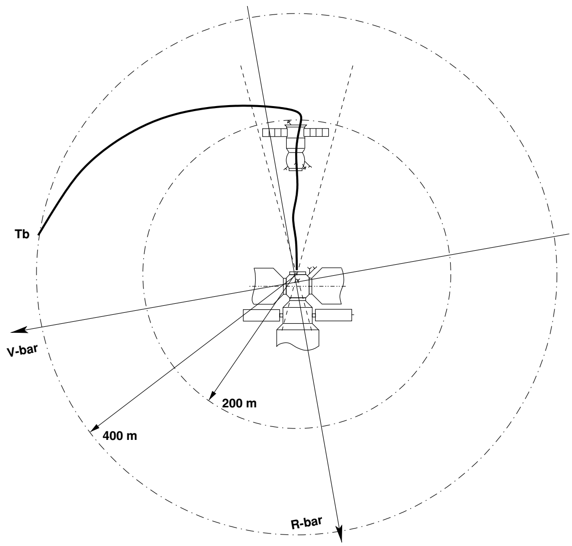

Figure B.8. Soyuz/Progress fly-around and final approach.

At the end of the standard for range approach (M8), the envisaged target docking port may point in a direction not aligned with the approach direction followed so far. In order to achieve alignment with the target docking axis, a fly-around is performed at a range between 400 m and 200 m, which will transfer the chaser to the required approach line for target docking ports on +V-bar, −R-bar or −V-bar, or to that of an inertially pointing port. This fly-around is a two-pulse transfer with components in radial and out-of-plane directions (see also figures 3.14, 3.17 and 3.18), depending on the direction of the docking axis. Considering the fact that both radial and out-of-plane transfers are cyclic motions, returning to the point of departure after one orbit, the impulsive fly-around has the important positive features of safety, repeatability and quasi-constant illumination conditions.

The latter feature can easily be understood considering the following example: starting an impulsive radial transfer with a ΔV at orbital dawn at the +V-bar side, the Sun will be behind the chaser vehicle, illuminating the target. This will continue along the trajectory until the chaser is at the −V-bar side and the Sun enters the shadow of the Earth. This behaviour does not change when an additional out-of-plane component is applied. The fly-around can be stopped at any time, whilst maintaining the same illumination conditions, which means that the docking port can be at any angle in the upper hemisphere.

After the fly-around, the vehicle will perform station keeping, whilst waiting for the go-ahead from the MCC; this waiting time will be utilised for the synchronisation of the final approach with the communication windows and the final adjustment of the illumination conditions. The final approach is a straight line closed loop controlled trajectory with a velocity profile of approximately 1 m/s at its start (150–200 m), which will be reduced to 0.1–0.3 m/s at contact.