2

The phases of a rendezvous mission

The purpose of this chapter is to give the reader a short overview of the different phases of a rendezvous approach and to describe the major issues of these phases. It is hoped that it will be easier, after familiarisation with the basic concept of a rendezvous mission, for the reader to put the information given in the subsequent chapters into their proper context. For this reason, some of the information provided in more detail in the later chapters had to be duplicated in condensed form here.

A rendezvous mission can be divided, as indicated in figure 2.1, into a number of major phases: launch, phasing, far range rendezvous, close range rendezvous and mating. During these phases, the kinematic and dynamic conditions that will eventually allow the connection of the chaser to the target spacecraft are successively established. In the following sections of this chapter an overview of the objectives, the end conditions to be achieved and the trajectory implementation possibilities of each of those phases will be given. This includes a rough order of magnitude of the major performance values which the guidance, navigation and control system of the chaser will have to achieve. For completeness, a short section on departure has been added, which addresses the issues and constraints of separation from and moving out of the vicinity of the target station. The mission phases between mating and departure and after departure are not addressed as they are both, in objective and concept, fully independent of the rendezvous mission.

2.1 Launch and orbit injection

2.1.1 The launch window

Owing to the rotation of the Earth, each point on its surface passes twice per day through any orbit plane. However, as a launch in an easterly direction produces a gain in launch

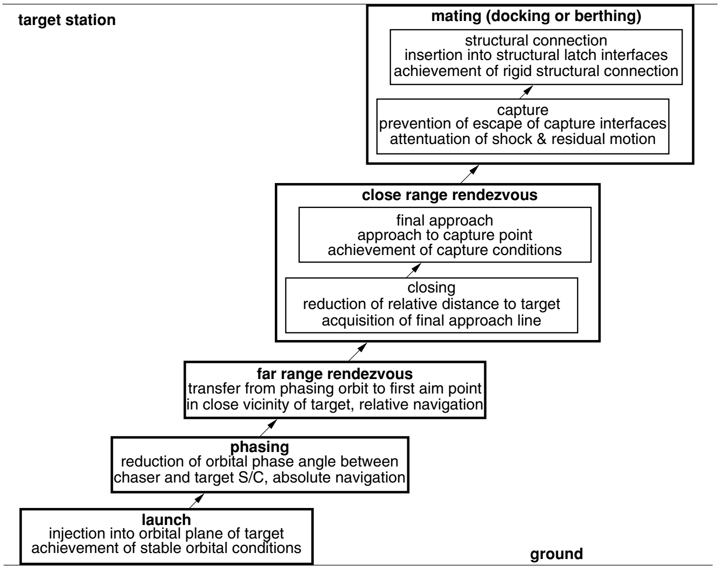

Figure 2.1. Main phases of a rendezvous mission.

velocity due to the tangential velocity component of the rotation of the Earth (≈463 m/s at the equator), and since at most launch sites only a limited sector of launch directions can be used (e.g. toward the sea), there is, practically, only one opportunity per day to launch a spacecraft into a particular orbit plane. With the Earth rotation of 15 deg/h, during every minute the launch site will move ≈0.25 deg w.r.t. the orbital plane (neglecting for the moment other drift effects). Plane differences resulting from a deviation from the nominal launch time can be most efficiently corrected by the launcher shortly after lift-off, when the relative velocities are still relatively low. A correction of the plane error in the final orbit would be much more expensive; e.g. at an orbital height of 400 km it would cost a ΔV of about 32 m/s to correct a 1 minute launch delay, see Eq. (3.20). Therefore, the size of the launch window, i.e. the margin around the time when the launch site passes through the orbital plane, will mainly be determined by the correction capabilities of the launcher.

2.1.2 Definition of orbit plane and other orbit parameters

Some brief definitions of concepts used in orbit mechanics are given here to provide the basis for the description of the rendezvous mission phases. A more detailed treatment is provided in chapter 3.

The direction in inertial space of the plane of an Earth orbit can be defined by two angles (see figures 2.2 and 2.3):

- its 'inclination' angle i, measured w.r.t. the equatorial plane of the Earth;
- the angle Ω w.r.t. a reference plane that is orthogonal to the equatorial one, but fixed in inertial space.

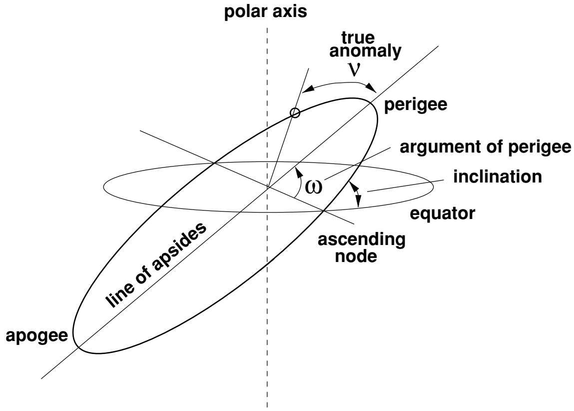

Figure 2.2. Definition of orbit parameters.

As the Earth rotates, one has to find a fixed point in space for the definition of this second reference plane. Convenient fix points for this purpose are the equinoctial points, defined by the intersection of the equatorial plane with the plane of the orbit of the Earth around the Sun (ecliptic).

The crossing points of a satellite's orbit plane with the equatorial plane are called the 'nodes'. The 'ascending' node refers to the point where the satellite is crossing in a northbound direction, and the 'descending node' refers to the southbound crossing point. This second angle, Ω, required for the definition of the orbit plane, is measured between the point of the vernal (spring) equinox and the ascending node (see figure 2.3). This angle is called the 'right ascension of ascending node' (RAAN).

An elliptic orbit is further defined by the size of its major (a) and minor (b) axes and by the location of its apogee and perigee w.r.t. the nodes (ω) or by corresponding expressions. The instantaneous position of a satellite on its orbit is defined by the 'true anomaly', which is the angle (ν) measured from the perigee of the orbit. These parameters are shown in figures 2.2 and 3.6.

2.1.3 Launch operations flexibility

In order to provide for sufficient flexibility of the launch operations, i.e. to provide as much margin as possible for possible interruptions of the countdown, one will attempt always to launch at the beginning of the launch window, whereas the nominal launch time will be in the middle of the launch window. The corresponding plane errors will

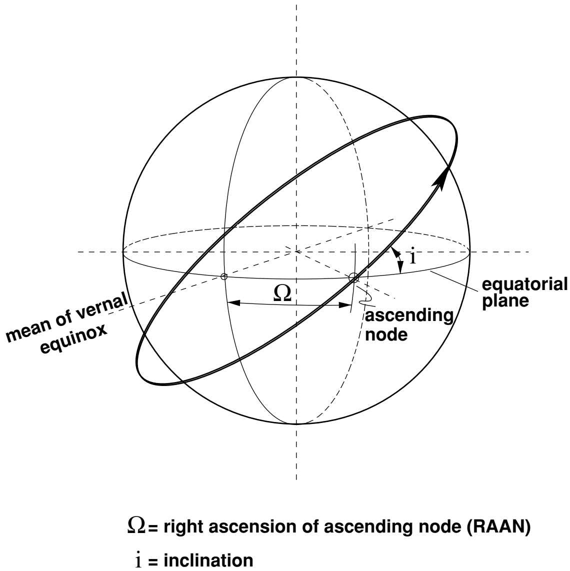

Figure 2.3. Definition of orbit plane.

be corrected, as discussed above, mainly during the early part of the launch phase. The subsequent phasing and rendezvous phases will also have to provide correction possibilities for residual launch dispersions, for achievement of the nominal arrival time and for other errors and perturbations.

2.1.4 Vehicle state at end of launch phase

At the end of the launch phase, the chaser vehicle has been brought by the launcher (and additionally, where necessary, by the spacecraft's own means of propulsion) into a stable orbit in the target orbital plane.[1] The chaser vehicle is then on a lower orbit and may be at an arbitrary phase angle behind the target (see figure 2.4) which depends on the orbit parameters of the target and on the actual launch date.

After separation from the launcher, the spacecraft has to deploy its solar arrays and antennas and must initialise all its subsystems. This phase may be particularly critical if the launcher injects the spacecraft into a non-viable orbit, i.e. into an orbit which would decay after a few revolutions. In this case it is of utmost importance that all necessary subsystems and equipment are in operation at the first apogee, so that a perigee raising manoeuvre can be performed.

[1] Actually, the chaser will be launched into a 'virtual' target plane, as the target orbit plane will drift with time; see section 5.2.1.

2.2 Phasing and transfer to near target orbit

2.2.1 Objective of phasing and state at end of phasing

The objective of this first orbital phase of a rendezvous mission is to reduce the phase angle between the chaser and target spacecraft (figure 2.4), by making use of the fact that a lower orbit has a shorter orbital period. During this phase, launch injection errors for inclination and RAAN will successively be corrected. As a rule, all phasing manoeuvres are controlled from ground. Phasing ends with the acquisition of either an 'initial aim point', or with the achievement of a set of margins for position and velocity values at a certain range, called the 'trajectory gate' or 'entry gate'. The margins of the 'aim point' or the 'gate' must be achieved to make the final part of the approach possible. The aim point or 'gate' will be on the target orbit, or very close to it, and from this position the far range relative rendezvous operations can commence.

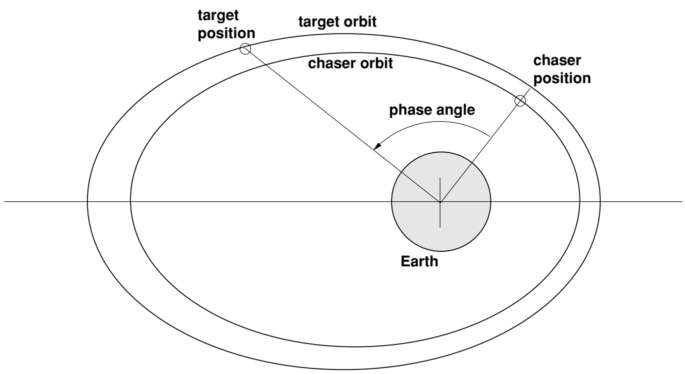

Figure 2.4. Definition of phase angle.

2.2.2 Correction of time deviations and orbit parameters

Depending on the phase angle to the target at the end of the launch phase, and given the time constraints for the total flight up to docking and the necessary correction of orbit parameters after launch, there is a multitude of possible phasing strategies, which will include the following choices of orbit and manoeuvre types:

- forward/backward phasing,
- circular/elliptic phasing orbits,
- change of orbit height in the case of circular orbits,
- change of apogee/perigee height in the case of elliptical orbits,
- lateral correction manoeuvres for inclination and RAAN corrections.

A more detailed discussion on the arrival time constraints of a rendezvous mission is given in chapter 5.

2.2.3 Coordinate frames during rendezvous

During launch and phasing, navigation is based on absolute measurements in an Earth-centred inertial frame. Trajectories of these phases will, therefore, usually also be represented in an Earth-centred frame, i.e. for the launch phase, when the desired orbital parameters have to be achieved, the 'Earth-centred equatorial frame' (see section 3.1.1), and for phasing, when the manoeuvres are mainly in the orbital plane, the 'orbital plane frame' (see section 3.1.2). During the far and close range rendezvous phases, when the trajectory evolution has to be shown in relation to the target position and over several orbital revolutions, it is more convenient to analyse the chaser motion in relation to the motion of the target and to represent it in a frame centred in the target and moving with it along the orbit. This is the 'target local orbital frame', defined in section 3.1.3. The curvilinear orbit direction is shown as a straight line and is named V-bar after the orbital velocity vector $\vec{V}$. The coordinate in the direction of the centre of the Earth is named R-bar after the radius vector $\vec{R}$, and the third coordinate completing the system is named H-bar after the orbital angular momentum vector $\vec{H}$. The centre of the system is the centre of mass of the target vehicle. As an example, figure 2.5 shows the trajectories of the target (target orbit) and of the chaser in both the orbital plane frame and the local orbital frame of the target. The chaser trajectory in this example is an eccentric orbit with an apogee on the target orbit and a perigee at a distance of Δh below it.

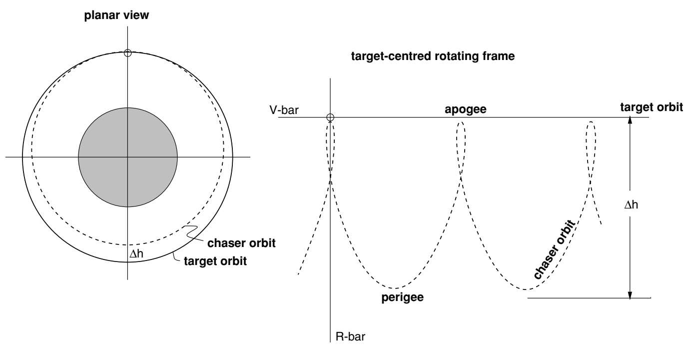

Figure 2.5. From planar view (inertial frame) to target-centred rotating frame.

2.2.4 Forward/backward phasing

When, at the time of the launch of the chaser, the phase angle to the target is too small (see figure 2.4), a direct transfer from the launch injection point to the target point may become too costly, as a forward phasing would need more than 360 degrees. This may have to be excluded because of mission duration constraints, e.g. due to battery power limitations or due to limitations of life support expendables in manned space missions. The propellant consumption for attitude control during the long phasing duration may also be a factor. In such cases, backward phasing may have to be considered. The chaser vehicle is then transferred to an orbit that is higher than the target one, where it will drift backward toward the target (see figure 2.6). Generally, one will try to avoid backward phasing because of the higher cost in terms of the ΔV needed to achieve the higher orbit.

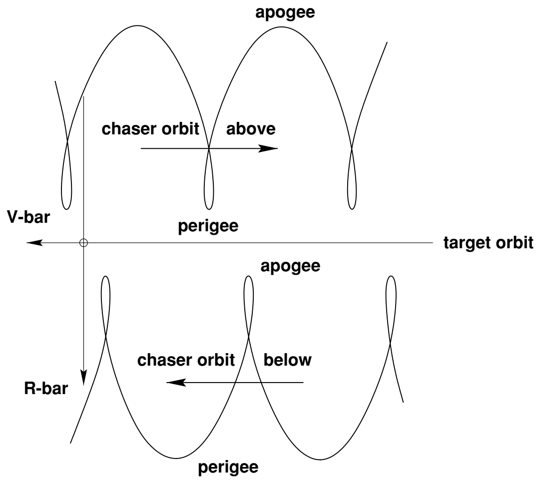

Figure 2.6. Forward and backward phasing below and above target orbit.

2.2.5 Different phasing strategy for each mission

Since for each launch day the phase angle conditions will be different, there can be no fixed phasing trajectories or strategies. Trajectories and manoeuvres will have to be calculated individually for each launch opportunity. For smaller phase angle uncertainties, arrival time adjustment can be achieved during flight by a strategy of drifting for different durations on orbits of different altitudes (see figure 5.22). With such a strategy, time deviations due to the constraints imposed by the launch window, or for example due to delays caused by operations of the target, can be compensated for. The problem of proper arrival time is addressed in more detail in chapter 5.

Figures 2.7 and 2.8 show two examples of possible phasing strategies. In the first strategy, both the apogee and perigee of the elliptic phasing orbits are raised at certain points in time, which slows down the phasing rate. The points at which the orbit is changed will be chosen such that the vehicle will arrive at the initial aim point at the proper time. If a global positioning system (GPS) receiver is available aboard the spacecraft, the necessary navigation and thrust execution accuracy is permanently available. In the second strategy, one attempts to raise the apogee of the chaser vehicle as soon as possible to the height of the target orbit. This requires, on the one hand, a higher thrust capacity, but, on the other hand, offers somewhat lower propellant consumption as well as the possibility of adjusting iteratively, based on ground measurements, the apogee of the chaser orbit to the orbital altitude of the target. Such a strategy has particular merits when autonomous onboard navigation is not available. The two examples show that the thrust capabilities of the vehicle and the available navigation means play a role in the selection of the phasing strategy. The perigee and apogee raising manoeuvres, along with Hohmann transfer manoeuvres, are discussed in more detail in section 3.2.2.

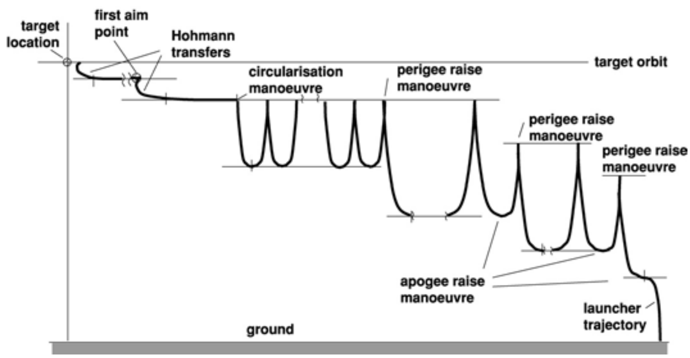

Figure 2.7. Phasing strategy.

2.2.6 Location of the initial aim point

The end point of phasing is often called the 'initial aim point' (see figure 2.7; see also point S0 in figure 2.9). This end point is, however, not a hold point. The location of this first aim point, i.e. whether it is on the + or − V-bar side, whether it is on or below/above the target orbit and whether it is at a larger or shorter distance from the target, will depend on a number of factors. The most important of them are the location of the docking port and the direction of the docking axis on the target and the operational range of the navigation sensor, which will be used for the subsequent first rendezvous phase (see section 5.3 for more details concerning the influence of port location and sensor characteristics on the approach strategy). Locating this point behind and slightly below the target is the most convenient solution, as the natural drift will move the chaser slowly toward the target without additional propulsion manoeuvres. During such drift, residual errors after the last manoeuvre in terms of Δ-height, Δ-eccentricity and out-of-plane errors (Δ-inclination and Δ-RAAN; for definition of these terms see section 3.2.1) can be corrected.

2.2.7 Strategy with entry gate instead of aim point

As already mentioned, instead of a scheme with a fixed aim point, a strategy with an 'entry gate' can be used for the transition from phasing to the far range rendezvous (see figure 2.8). In this strategy, first the apogee is raised to the height of the target orbit, then the perigee is raised successively, reducing the phasing rate. The final goal of phasing is the passing through the entry gate, which fulfils the conditions for the start of far range rendezvous operations in terms of x,y,z positions and velocities. This strategy is convenient when a phasing strategy is used, in which the apogees of all orbital revolutions are on V-bar and when a continuous approach without interruptions is planned. In this case, the 'gate' conditions are applied for the last apogee prior to the final rendezvous operations.

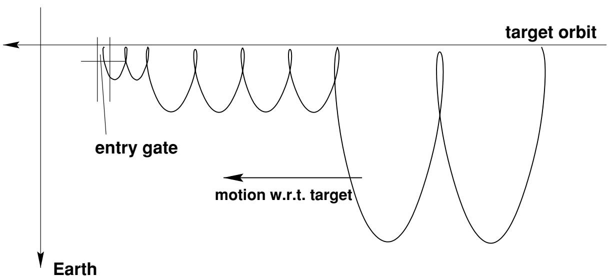

Figure 2.8. Alternative strategy: entry gate.

2.2.8 Final accuracy of open loop manoeuvres

Manoeuvres during phasing are usually performed in open loop, i.e. first the manoeuvre is calculated, then it is executed, and the achieved result is verified thereafter. As typical two-pulse manoeuvres have only limited accuracy, it may be necessary to perform several consecutive manoeuvres at the end of phasing to achieve the required accuracy for the initial aim point or entry gate for far range rendezvous. For reasons of safety (risk of collision with the target), most critical will be the achievement within close tolerances of the proper orbital height, in circular orbits, or of the apogee height, in elliptical orbits. The positioning accuracy, which eventually can be achieved on the basis of absolute navigation by open loop manoeuvres, e.g. by a Hohmann transfer, is typically of the order of a few hundreds of metres in height and a few kilometres in orbital direction. The errors arising from such open loop manoeuvres are discussed in section 4.3.

2.3 Far range rendezvous operations

2.3.1 Objectives and goals of far range rendezvous

In many publications this phase is called 'homing', by analogy to the navigation term used for aircraft when approaching an airport. The major objective of the far range rendezvous phase is the reduction of trajectory dispersions, i.e. the achievement of position, velocity and angular rate conditions which are necessary for the initiation of the close range rendezvous operations. Major tasks of this phase are the acquisition of the target orbit, the reduction of approach velocity and the synchronisation of the mission timeline. Far range rendezvous can start when relative navigation between chaser and target is available. The end point of this phase (see point S2 in figure 2.9) is usually a point from which standard rendezvous operations on standard trajectories at a fixed timeline can commence, a feature which is particularly desirable for an automatic rendezvous process.

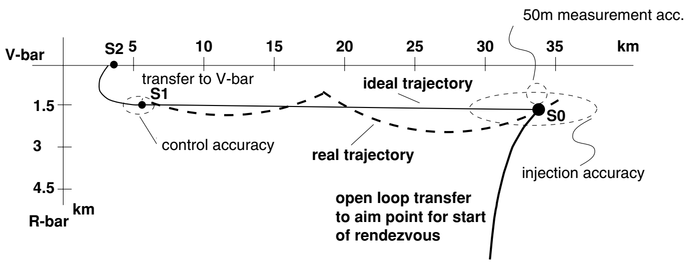

Figure 2.9. Transfer from phasing orbit to rendezvous drift orbit.

A constraint on the location of the end point of the far range rendezvous may result from operational requirements imposed by the target station. For example, for the ISS an 'Approach Ellipsoid' is defined with a major half-axis of 2 km along the target orbit direction and minor ones of 1 km (see section 5.6, figure 5.24). The requirement is that the approach initiation for final rendezvous manoeuvres should be located outside the Approach Ellipsoid. As a result, far range rendezvous typically starts in this scenario at a range of a few tens of kilometres and ends at a range of few kilometres from the target.

2.3.2 Relative navigation during rendezvous

Whereas during phasing all manoeuvres are based on absolute navigation measurements, provided either by sensors aboard the chaser (e.g. GPS) or on ground, navigation during rendezvous operations proper (i.e. far range and close range rendezvous) is based on relative measurements of range and direction (e.g. radar) or directly by the relative position (e.g. relative GPS or RGPS) between chaser and target vehicles. The final open loop manoeuvres at the end of phasing must lead to conditions which bring the chaser into the acquisition range of the relative navigation sensor for far range rendezvous (for types and details of navigation sensors, see chapter 7). The required measurement accuracy of the relative navigation sensor at the beginning of the far range rendezvous phase is of the order of 100 m. In the same way, the accuracy of the last part of the far range rendezvous trajectory must be commensurate with the requirements for the start of the close range rendezvous operations. The required positioning accuracy is typically of the order of a few tens of metres and the measurement accuracy is of the order of 10 m.

2.3.3 Trajectory elements/time-flexible elements

Trajectory elements during far range rendezvous may include free drift trajectories on circular or elliptic orbits, tangential and radial transfers (see section 3.3.2) and hold points (see section 3.3.3). In order to be able to synchronise the mission timeline with external events, such as Sun illumination, communication windows and crew operations timeline, the far range rendezvous strategy may need to include 'time-flexible' elements. We have identified such a time-flexible element already during phasing, where faster and slower phasing rates could be achieved by varying the orbital height. Although this technique can be used here as well, other time-flexible elements become possible because the chaser is now close to target orbit. The most important one is, of course, a hold point on the target orbit, where the vehicle can stay indefinitely at nominally zero ΔV costs. If such a hold point on V-bar is used, it is usually implemented at the end of the far range rendezvous phase (figure 2.10). Other possibilities include forward and backward drifts below or above the target orbit, or an elliptical motion with the mean orbital height equal to the target orbit. For more details on time-flexible elements, see section 5.4.4.

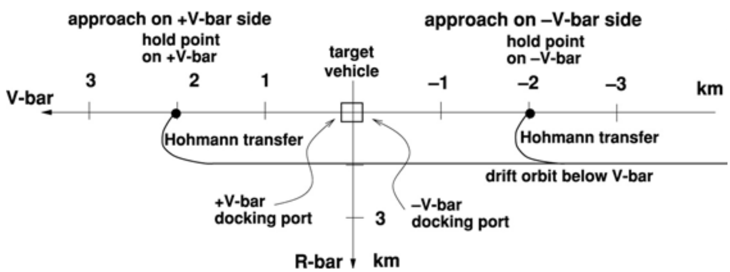

Figure 2.10. Time-flexible element: hold point on V-bar.

2.3.4 Communication with the target station

Generally prior to or shortly after the start of the far range rendezvous phase, communication between chaser and target vehicles will be established. Communication capability between the two vehicles may be required for operational and safety reasons and possibly also for navigation sensor functions (e.g. for RGPS). In fact, apart from the possible communication requirements for the sensor function, the complete approach up to mating could be conducted without communications between the vehicles, i.e. all communications going via ground. However, as the communication links with ground are more prone to disturbances and black-outs, in rendezvous missions with manned target vehicles safety considerations require the establishment of such links prior to the start of close range rendezvous operations. The target crew must be able to monitor the trajectory and attitude of the incoming vehicle and must be able to command the chaser to stop or retreat in case of problems with either chaser or target vehicle. The crew must also be able to initiate a collision avoidance manoeuvre in case of dangerous trajectory situations. As a result, direct communication between the vehicles is not necessarily a requirement in cases where both vehicles are unmanned.

2.4 Close range rendezvous operations

The close range rendezvous phase is usually divided into two subphases: a preparatory phase leading to the final approach corridor, often called ‘closing’, and a final approach phase leading to the mating conditions. There are, of course, cases where no distinction can be made between a closing and a final approach subphase. This may be the case, e.g., for a V-bar approach, where the direction of motion remains the same and where no change of sensor type occurs.

The following features are important for the initiation of close range rendezvous operations: out-of-plane errors (inclination, RAAN) have been corrected to the same accuracy as the in-plane errors; the mission timeline up to capture has been synchronised with the external constraints; and all parties involved, i.e. space and ground segment of both vehicles, are ready for the final operation up to mating. The proximity to the target makes all operations safety-critical, requiring particular safety features for trajectory and onboard system design and continuous monitoring and interaction possibility by operators on ground and in the target station.

2.4.1 Closing

Objectives and end conditions of closing

The objectives of the closing phase are the reduction of the range to the target and the achievement of conditions allowing the acquisition of the final approach corridor. This means that at the end of this phase the chaser is, concerning position, velocities, attitude and angular rates, ready to start the final approach on the proper approach axis within the constraints of the safety corridor. If the approach axis for mating is not in the + or − V-bar direction, the closing phase may include a fly-around manoeuvre to acquire the approach axis. Because of the increased navigation accuracy requirements, in many cases a different type of sensor than in the previous phase has to be used for the final approach. In this case, toward the end of the closing phase, the acquisition conditions for the new sensor type have to be met. The rule of thumb is that the measurement accuracy must be of the order of 1% of range or better.

Trajectory elements/time-flexible elements

Because of the safety criticality of the close range rendezvous operations, trajectory strategies have to be conceived such that the incapacity to execute a thrust manoeuvre, whether fully or partially, does not leave the vehicle on a trajectory which eventually leads to a collision. The following observations are relevant for the choice of trajectory in the closing phase.

- Because of their resulting trajectory characteristics, pure tangential thrust manoeuvres are rarely used (see figures 4.11 and 4.12).
- Radial manoeuvres result in eccentric orbit trajectories without changing the average orbital altitude, i.e. in stationary ellipses when initiated on V-bar (see figure 4.13). However, when they are, e.g., due to navigation errors initiated at a position which is higher or lower than the target orbit, they will result in 'walking ellipses', moving toward or away from the target. This problem and possible counter measures are discussed in more detail in section 4.4.2.
- If the closing phase extends over around 2000 m, straight line approaches are not used because of the comparatively high ΔV costs.

It must be ensured that if trajectory control ceases, there will be no risk of colliding with the target for at least a number of revolutions. The number of collision-free revolutions required will depend on the time the target vehicle needs to prepare and execute an escape manoeuvre.

Although the mission timeline is assumed to be already synchronised with external constraints prior to start of closing, time-flexible elements in the form of hold points may still be needed for fine-tuning and for operational reasons. Another consideration is that the rendezvous process may have to be interrupted for some larger time because of contingencies arising at either vehicle. In this case, the chaser vehicle may need to return to a hold point at a safe distance, where it can wait until the approach can be resumed. Trajectory design will, therefore, have to take into account the return to such a hold point. This can be, e.g., the point from which the closing trajectory is started or a safer point at larger distance from the target, if resolution of the contingency is expected to take more time.

Fly-around and direct R-bar acquisition

The different acquisition strategies for V-bar and R-bar approaches are shown in figure 2.11. Final approaches on V-bar (trajectories (a) and (b)), can commence directly from a V-bar hold point on the + or − V-bar side (trajectories (a) and (b)). For the acquisition of an R-bar approach corridor, several possible strategies can be employed.

- The first is a fly-around starting from a position on V-bar (trajectory (c)). The advantage of starting from a V-bar position is the operational flexibility due to the possibility of an unlimited stay time at a V-bar hold point.
- The second is to acquire the starting point of the R-bar trajectory directly from an orbit lower than the target orbit (trajectory (e)), making use of the natural upward motion at the end of a radial impulse transfer trajectory. This strategy has the advantages of a short approach time and low propellant propulsion, as intermediate trajectories are omitted; however, there are disadvantages of no time flexibility and less favourable collision safety features.
- The third possibility is trajectory (d), which is a drift toward the R-bar approach corridor on a slightly lower orbit than the target orbit and has the advantages of a lower propellant consumption and inherent collision safety of the trajectory. By selection of the altitude difference to the target orbit, a certain amount of time flexibility can be achieved.

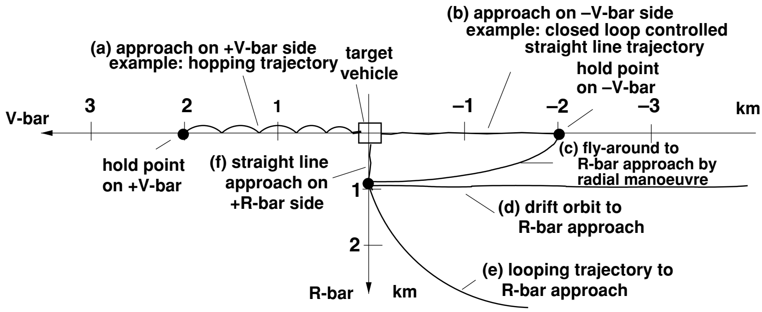

Figure 2.11. Acquisition of V-bar and R-bar final approach.

The eventual choice of acquisition strategy for an R-bar approach will depend on many safety constraints (see chapter 4) and operational constraints (see chapter 5).

2.4.2 Final approach to contact

Objectives and end conditions of final approach

The objective of the final approach phase is to achieve docking or berthing capture conditions in terms of positions and velocities and of relative attitude and angular rates. The attempted end condition is the delivery of chaser docking or capture interfaces into the reception range of the target docking mechanism or of the capture tool of the manipulator in the case of berthing. In the case of passive capture latches (impact docking), there must be a certain axial contact velocity, as the energy is needed to operate the capture latches. In the case of active capture latches (soft docking), the capture latches are motorised and triggered by sensors. This type of docking mechanism will work also with very low contact velocities (see sections 8.3.4 and 8.3.5). For berthing, the capture interface for the manipulator, mounted on the chaser, must remain for a certain duration within a volume which can be reached by the manipulator within that time.

Trajectories during final approach

The trajectory types used for the final approach are closed loop controlled straight line trajectories or quasi-straight line trajectories realised by a multitude of small hops (see figure 2.11, trajectory (a)). The first type is the preferred choice for automatic onboard control systems, whereas the latter is more convenient for man-controlled approaches, as fixed thrust pulses can be commanded, e.g. when a reference line of the target image crosses the horizontal centre line of the field of view of a camera or sensor. Straight line or quasi-straight line trajectories are preferred during this phase, on one hand because of the limited field of view of the rendezvous sensors, and on the other hand because the docking interfaces have to enter each other along their symmetry axes.

Navigation and control requirements

The rule of thumb for the navigation measurement accuracy of approximately 1% of the range can, for a preliminary assessment, also be applied for the final approach. It is compatible with the final control accuracies for docking, which are, depending on the reception range of the docking mechanism, a few centimetres in lateral position, about 1 deg for attitude and of the order of 1 cm/s for axial and lateral rates and 0.1 deg/s for angular rates.

For berthing, the absolute position and attitude accuracies are less critical, i.e. values approximately a factor of 5 higher than those for docking may be still acceptable. In contrast, linear and angular rates must be a factor of approximately 5 lower than those acceptable for docking. For safety reasons, the target station may require that the reaction control system of the incoming vehicle is switched off prior to the start of the grappling operations by the manipulator. The manipulator operations from initiation until capture may take more than 60 s, within which time the grapple interfaces of the incoming vehicle must remain in the capture range. This is one of the reasons why berthing conditions may be more difficult to achieve by the GNC system than docking conditions (cf. section 5.3.1).

For docking, the GNC system has to fulfil an additional condition. The V-bar and R-bar approach axis, discussed so far, concern the nominal docking axis. The actual docking axis will deviate from the nominal direction due to (i) attitude bias, (ii) attitude control motions, and (iii) bending of the structure of the target vehicle. It is, therefore, important that the chaser vehicle acquires and follows the instantaneous docking axis (see figure 2.12). This is possible only when the chaser has the navigation means to identify and track the centre of the docking port and the direction of the docking axis. For this purpose the rendezvous sensor for the final approach must be able to measure, in addition to axial and lateral positions (or range and direction), the relative attitude between the docking ports of chaser and target (see section 6.2.3, figure 6.12). This requirement does not exist for berthing.

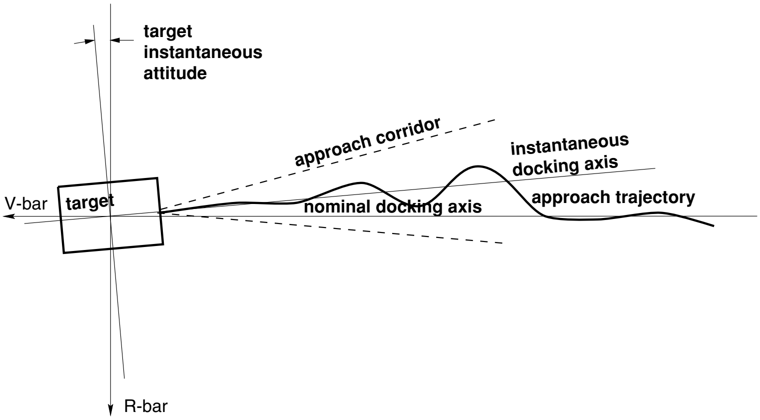

Figure 2.12. Acquisition of instantaneous docking axis.

Other constraints during final approach

For observability and safety reasons a cone-shaped approach corridor will usually be defined, within which the approach trajectory has to remain. The cone originates from the mating point at the target vehicle, i.e. from the docking port or from the berthing box, and has a half cone angle of 10–15 deg. Such a corridor allows ground operators and/or target crew to assess via video cameras or other sensor information the accuracy of the approach trajectory. If corridor boundaries are violated, stop, retreat, or collision avoidance manoeuvre commands can be issued (for further details concerning approach safety, see chapter 4).

Another issue which plays an important role when the approaching vehicle comes close, is the effect of the thruster plumes on the target vehicle. Three major effects can be distinguished:

- the forces exerted on the target vehicle by the plume pressure;
- the heat load on the structure of the target vehicle by the hot plume gases;
- the contamination of the surface of the target vehicle by the combustion products and unburned propellant components.

In order to reduce the approach velocity, the approaching vehicle has to apply forces in the opposite direction, i.e. it has to thrust directly toward the target. In addition, the attitude of the vehicle has to be controlled, resulting in thruster burns in all directions. The resulting effects on the target vehicle from the thrust plumes of the chaser can be:

- disturbance of the attitude and position, depending on the mass and inertia of the target in relation to the plume pressure;
- overheating of parts of the surface and underlying structure;
- contamination of sensitive elements on the target surface, in particular of optical elements, such as the target reflectors for the rendezvous sensor and the lenses on monitoring cameras, and of, e.g., the sealing elements of the docking mechanism.

In order to minimise these effects, for docking the final contact velocity will be achieved at some distance from the target and will thereafter be kept constant. The final braking burn toward the target then takes place at a distance which is far enough away such that the gas temperature has sufficiently cooled to avoid damage of the structure, and such that the density of contaminating particles is sufficiently reduced to avoid significant condensation when arriving at the target surface. For berthing, these effects are less pronounced, as the berthing box will always be located as far away from the target structure as the reach of the manipulator arm allows.

2.5 Mating: docking or berthing

2.5.1 Objectives and end conditions of the mating phase

The mating phase starts when the GNC system of the chaser has delivered the capture interfaces of the chaser into the reception range of those of the target vehicle. This must be achieved within the constraints of the interface conditions, concerning

- approach velocity, lateral alignment, angular alignment, lateral and angular rates for docking;
- position and attitude accuracy, residual linear and angular rates for berthing.

It is then the task and responsibility of the mating system to:

- achieve capture, i.e. the condition of no escape (task 1);
- attenuate the residual relative motion between the vehicles (task 2);
- bring the interfaces of the structural latches into their operational range (task 3);
- achieve rigid structural connection (task 4);

- achieve gas-tight sealing of the connection of a pressurised passage between the vehicles (task 5) – this is achieved usually in connection with the process of structural connection;
- establish the connection of data, power and possibly of fluid (propellant, water, air supply) interfaces (task 6).

Docking and berthing operations to achieve these tasks are described in sections 8.1.1 and 8.1.2. When these tasks are fulfilled, the mating phase is concluded. The subsequent phase of joint operations is outside the scope of this book.

2.5.2 Capture issues

In docking, all tasks are concentrated in one system, the docking mechanism. In berthing, tasks 1, 2 and 3 are performed by a manipulator arm, and the residual tasks are performed by a berthing mechanism. Another difference between docking and berthing is that the capture interface for berthing, the so-called grapple fixture, does not need to be located on the chaser vehicle in the vicinity of the other mating interface elements. In fact, for better acquisition and handling it is usually located in a different plane on a different part of the surface of the vehicle.

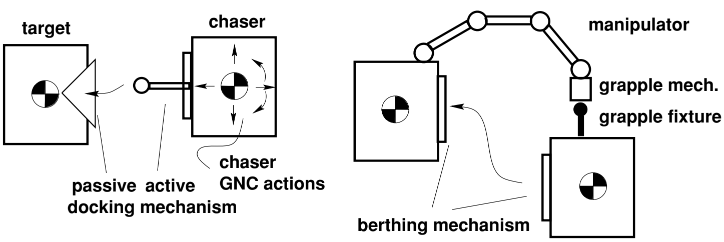

Figure 2.13. Docking and berthing.

For the purpose of this chapter, the most important mating function is capture, as it is the natural end of the rendezvous process. The subsequent structural and utility connection tasks are, for the success of the mission, of no less importance; however, they are independent from the dynamic processes of approach, contact and capture. The connection tasks will be addressed in section 8.4.1.

The basic difference concerning capture between docking and berthing is that in docking the body of the approaching vehicle is actively controlled to guide its capture interfaces into the corresponding interfaces on the target vehicle. In berthing, the manipulator arm plays the active role, guiding its grapple mechanism to capture the passive grapple fixture on the other vehicle. As a matter of fact, the manipulator arm can be located on either the target station or the approaching vehicle, and vice versa for the passive grapple fixture. The basic differences between the docking and berthing processes are illustrated in figure 2.13. The physical effects at the contact and capture interfaces are, however, very similar.

Since at contact the two bodies will rebound and will separate again (see figure 2.14), capture must be accomplished in the short time before the interfaces have left the capture volume. For example, in the case of free motion of a rigid body with a relative velocity of 0.1 m/s into a concave cone of a fixed body with an opening diameter of $d = 0.1$ m, the body would leave the cone again after two (perfect) rebounds within 1 s (see figure 2.14). The methods of how to achieve capture under such conditions and how to increase the time for capture will be discussed in more detail in section 8.3.

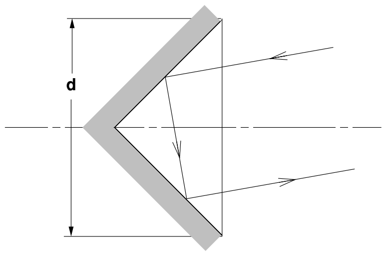

Figure 2.14. Rebound trajectory in a concave cone.

2.6 Departure

2.6.1 Objectives and end conditions of the departure phase

All rendezvous missions, except for assembly missions, will eventually include the separation and departure from the target spacecraft. This phase includes the re-initiation of the GNC system, the opening of the utility and structural connections and the departure from the target station. The end conditions of this phase are that the departing vehicle moves on a non-returning trajectory, and has arrived at a sufficiently safe distance w.r.t. the station, when the large thrust manoeuvre for de-orbitation will be performed.

2.6.2 Constraints and issues during departure

After the opening of the structural latches, an impulse has to be applied to the centre of mass (CoM) of the departing vehicle (assuming the target station remains passive) to achieve the necessary departure velocity. This is generally the task of the propulsion system of the departing vehicle. However, an impulse large enough to achieve the required safe departure trajectory implies a relatively large thrust in very close proximity to the target vehicle surface. The potential effects in terms of thermal loads and surface contamination have already been addressed in section 2.4.2. Solutions to this problem may include, as first manoeuvre steps, the application of spring forces at release of the structural latches, providing the impulse for the first few metres of motion, and thereafter the application of thrusts in a direction orthogonal to the docking port direction. Another constraint is the requirement for observability of the departure trajectory by a sensor or video camera, in the same way as for the final approach. This leads to the definition of a departure corridor analogous to the docking corridor.

A typical trajectory and corridor for departure from a $-$V-bar docking port is shown in figure 2.15 and for departure from an R-bar port in figure 2.16. The manoeuvre strategy in both examples fulfils the requirement of minimum plume impact on the target station and trajectory inside the departure corridor.

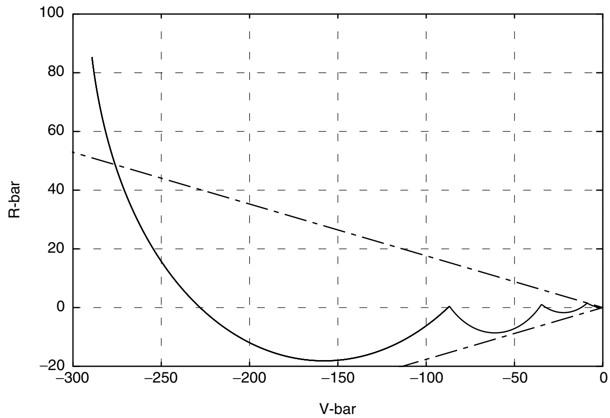

Figure 2.15. $-$V-bar departure.

The V-bar departure strategy shown in figure 2.15 assumes a first small ΔV of 0.06 m/s applied to the departing vehicle by the springs of the docking mechanism. The resulting trajectory would soon leave the departure cone, which has been assumed to have a half cone angle of 10 deg. The first impulse by the propulsion system after 150 s is a thrust of 0.05 m/s in the $-$R-direction to minimise the plume impact on the station. A further radial manoeuvre of -0.08 m/s follows after 420 s to keep the vehicle inside the departure corridor. After a further 720 s, at a distance of $\approx$80 m, a combined radial and axial boost of -0.2 m/s each can be applied without too much impact by the plume on the station. A departure corridor is usually defined for a distance of a few hundred metres, after which the departure trajectory is free to assume any shape, as long as it is moving away from the target.

The first elements of the trajectory in such a departure corridor are not inherently safe, since, in the case of loss of control capability, the resulting free drift trajectory would lead to collision with the target station. In this case, as a last resort, a collision avoidance manoeuvre (see section 4.5) must be initiated, for which, of course, potential plume effects must be acceptable for the target. The corresponding departure trajectory on the $+$V-bar side can be obtained by mirroring the $-$V-bar trajectory on the R-bar and V-bar axes.

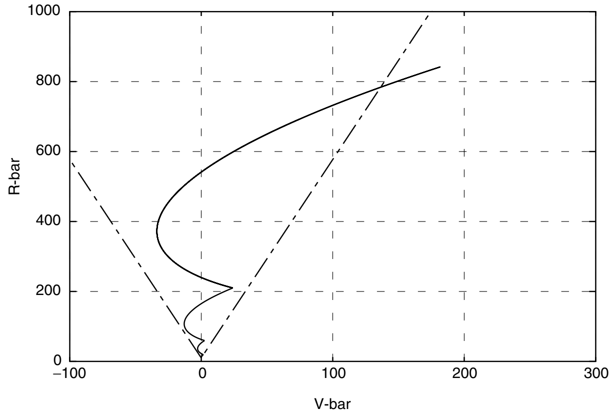

Figure 2.16. R-bar departure.

The departure from an R-bar docking port or from a berthing location is somewhat less critical concerning trajectory safety and contamination. Due to the fact that the CoM of the departing vehicle will be below V-bar, the natural motion after release of the structural latches will be downward and forward (figure 2.16). In order to remain in the departure corridor, the first thrusts, as well as the final departure burn, will be in the $-$V-bar direction, i.e. not toward the target surface, as in the case of the V-bar departure.

In the example it is assumed that the CoM of the departing vehicle is 10 m below the CoM of the station and receives a ΔV of 0.06 m/s from the springs of the docking mechanism. This results in a position change in the + R-bar direction of $\approx$1.7 m after 300 s. At that point, a small thrust manoeuvre in the $-$V-bar direction of 0.06 m/s is applied. Thereafter, further $-$V-bar thrusts may have to be applied in order to keep the trajectory inside the departure corridor. Only at a distance of $>$200 m can the final departure manoeuvre be applied. This will be a large boost in the $-$V-bar direction.

In contrast to the approach, the required accuracy of the departure trajectory is decreasing, and there is in principle no need for a departure cone as narrow as that given in the two examples. The departure cone axis could even be at an angle w.r.t. V-bar, better following the natural motion. To monitor trajectory safety, the departure cone must be, however, in the field of view of the observation camera.

As shown in this section, departure strategies are formed by two or more impulsive manoeuvres and are therefore simple and straightforward. Since the complexity of the departure process in terms of trajectory implementation is comparatively low, and, accordingly, sensor and GNC requirements are fully covered by the relevant discussions for the approach phase, the rest of the book can concentrate on the rendezvous phases only.