9

Space and ground system setup

This chapter addresses the tasks and responsibilities of all parties outside the automatic onboard system involved in the control of a rendezvous mission. It looks at the hierarchy of authority, the support functions required and the constraints imposed by the communication links. Tasks and design principles of support tools for human operators are indicated.

As discussed already in chapter 6, in an Earth orbit there is no need to conduct the rendezvous and docking process fully autonomously. The interaction by external operators is, on the contrary, always desirable, when this will reduce the complexity of the system and increase safety and success probability. On the other hand, because of the limitations of the communication links, the complete control of the rendezvous and docking process cannot be performed entirely from ground. For this reason, the onboard control system of unmanned spacecraft must be able to perform automatically in the vicinity of the target vehicle the control tasks discussed in chapter 6:

- the control of the spacecraft state (attitude angles, position, velocities and angular rates);
- the sequencing of manoeuvres and modes at the right time and points of a trajectory;
- the detection of, and recovery from, anomalies and failures;
- in the case of docking, sequencing and control of mating operations.

A number of high level control tasks can be performed better by remote human operators, who can contribute the human capabilities of recognition and assessment of unpredicted situations, together with the much larger resources for information gathering and data processing than are available to the onboard system. Remote operators will, therefore, monitor the trajectory and attitude of the vehicles, the status of the automatic onboard systems and of the communication links; command, e.g., equipment reconfigurations or manoeuvres in case of contingencies not resolved by the onboard system; and will re-plan the mission in case of deviations from the planned timeline due to delays or contingencies. Remote operators with their support tools will be in a better position than the onboard system to identify failures and to find the best solutions for long term recovery measures.

9.1 Functions and tasks of space and ground segments

The remote interaction by operators on ground and in the target station will include in the nominal case (a) monitoring and high level control of spacecraft functions and of the spacecraft state vector and (b) the initiation of manoeuvres or the next step in the automatic approach. The ground segment will, in addition, provide operational data to the spacecraft, such as the actual orbit ephemeris of both vehicles. After launch and during phasing, only attitude control and housekeeping functions are controlled automatically by the onboard system; all manoeuvres are planned, calculated and initiated from ground. In contrast, during the rendezvous phases, ground involvement is in the nominal mission mode generally reduced to monitoring and to high level decision making, e.g. approach initiation or command of holds, etc. The ground segment will have to assume a more active role if there are deviations from the nominal mission plan. If there are mission interruptions or delays, the most important task of the ground operators will be the re-planning of the mission sequence. In the case of onboard failures, the major task will also be the identification of the failure source and, if a failure situation cannot be resolved by the onboard system, immediate moderation of the situation and the initiation of recovery actions.

9.1.1 General system setup for a rendezvous mission

The general system setup of the space and ground segments of chaser and target is shown in figure 9.1. It is assumed here that each vehicle has its own control centre (CC). However, in cases where the chaser and the target are operated by the same authorities, a part or all of the ground segment functions of both vehicles may be performed by the same centre. In this case, each of the vehicles will probably have its own control team.

Chaser and target vehicles can be controlled independently during the mission phases of launch and phasing (figure 9.2). Except for mutual exchange of information concerning mission progress, only one type of data is required by the chaser CC from the target CC, i.e. the precise orbital parameters of the target station. As these parameters will change over time, regular updating will be required. All this information exchange can be performed off-line, e.g. by voice or electronic mail communication, as there is no need, at this stage, to involve the partner in the space–ground data stream of the other vehicle.

From the end of phasing onwards, when the chaser is transferred to an orbit close to that of the target (e.g. to an 'initial aim point'), continuous information exchange

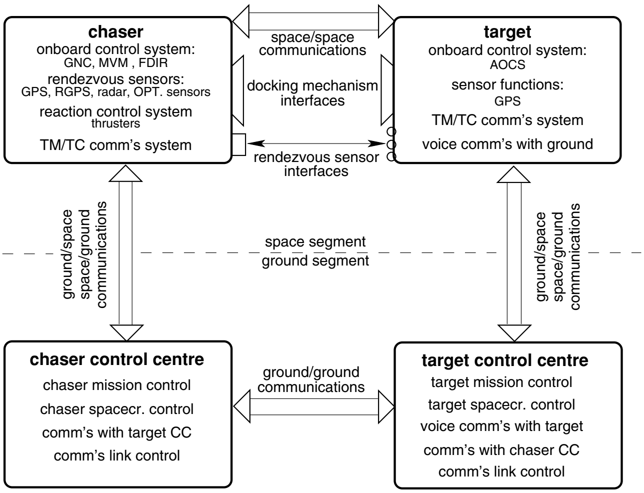

Figure 9.1. System functions and interfaces in a rendezvous mission.

between the two control teams is required. At this stage of the mission, space–space communication links between chaser and target have to be established and verified, operational schedules of both vehicles have to be synchronised, manoeuvres and trajectories of the chaser have to be assessed concerning collision safety, and decisions concerning continuation of the nominal approach at hold points or 'gates' have to be made jointly by the chaser and target control centres. During proximity operations, i.e. starting from a distance where the target or a safety zone around it (see figure 5.24) could be reached within the next following manoeuvre, a control hierarchy must be put in place which coordinates the operations of chaser and target space and ground segments (figure 9.3). One of the control centres must then have the lead concerning decisions on the further approach. In the case where an unmanned vehicle is the chaser and a manned space station is the target, the highest authority must be with the control centre of the manned vehicle, i.e. the target. In contrast, if the chaser is a manned vehicle, the highest authority will probably be with the chaser CC, as the chaser has the better manoeuvring capability.

During all phases of a rendezvous mission, each control centre will be responsible for monitoring and control of the subsystems and of all hardware and software of its own vehicle. After mating, the control centre of the target vehicle will, in a space station scenario, have the authority over the joint complex. In other cases, where the target is smaller, has less control intelligence on board, or is unmanned and the chaser is manned, the situation may be reversed. The various types of responsibilities and authorities during the rendezvous process are discussed in more detail below, after identifying the tasks which have to be performed by the ground segment during the mission.

Concerning the control of the approach and capture process, the major tasks of the chaser CC in the different phases of a rendezvous mission are as follows.

- After launch and during phasing:
  - preparation, initiation and verification of all manoeuvres.
- During the nominal rendezvous phases:
  - monitoring of manoeuvres/trajectories controlled by the onboard system;
  - issuing of 'go-ahead' commands for approach continuation at hold points.
- During capture:
  - monitoring of the capture process in the case of automatic docking.
- In case of contingencies:
  - issuing of commands for approach interruption in non-safety-critical contingencies;
  - issuing of commands for a CAM, in the case of major malfunctions of the onboard system, or of major trajectory deviations, which may lead to collision danger (if a CAM has not been executed by the onboard system);
  - preparation and implementation of recovery actions after CAM or mission interruptions.

It should be pointed out that various approach scenarios including all conceivable contingency cases will have to be worked out in detail, during mission planning prior to launch. The contingency actions to be taken by ground controllers and station crew must be well documented and agreed on by all parties, such that each individual knows immediately how to respond. However, not all types of contingencies can be foreseen, and not all recovery actions can be pre-planned. For the follow-on steps, *ad hoc* decisions may have to be taken.

In addition to the trajectory control tasks, the chaser CC has to perform a number of other tasks related to the control of the spacecraft and the space and ground infrastructure. The most important of these tasks are:

(1) monitoring and control of chaser spacecraft onboard systems and equipment;

(2) communication with the ground segment of the target;

(3) control of the communication links.

The first of these tasks is, in principle, no different from the ground control tasks for single spacecraft, except for the monitoring of the rendezvous specific onboard systems. Similarly, the third task is, in principle, no different from that for other space missions, except for control of the communication links to the target CC. The communication and close cooperation with the control centre of another vehicle is, however, a new rendezvous specific task, which also includes the new problem of arrangement of the hierarchy of control authority.

Assuming a rendezvous mission between an unmanned chaser vehicle and a manned space station, the major tasks of target ground segment (target CC) during the rendezvous mission would be as follows.

- After launch and during phasing:
  - monitoring of the chaser's mission progress, using data provided by the chaser CC.
- During the nominal rendezvous phases:
  - preparation of target spacecraft for final rendezvous and mating phases;
  - involvement in 'go-ahead' decisions after hold points;
  - monitoring of final approach trajectory, capture and structural connection.
- Control of the joint complex after attachment of the chaser.

The tasks to be performed by the target CC during the rendezvous phases require detailed information on the chaser state vector and, for docking, on the functional status of the docking mechanism of the chaser.

In the last part of the approach in a space station scenario, the target crew also must possess all the available information on the trajectory and attitude of the chaser vehicle. Therefore, in the rendezvous phases these data will be transmitted on the local link from the chaser to the target station and then, together with the target data stream, to the target CC.

9.1.2 Control responsibilities and control hierarchy

From the above listed tasks, which have to be performed during the rendezvous phases by the remote operators in the chaser and target CC and in the target station, different types of responsibilities can be identified and a control hierarchy may be derived. The responsibilities of the various parties can be generally grouped into four categories:

(1) responsibility for proper operation and health of onboard functions of a vehicle;

(2) responsibility for initiation and execution of manoeuvres, for change of trajectory and attitude of a vehicle;

(3) responsibility for safety monitoring regarding collision danger and for initiation of collision avoidance actions if necessary;

(4) responsibility for mission plan execution and for mission re-planning.

Control responsibility for the onboard system

All remote operations related to the proper functioning of the onboard systems will remain, during the entire mission, the responsibility of the specific control centre of each vehicle. Such operations will include, e.g., the checking of hardware and software functions, failure identification following warnings or automatic redundancy switching by the onboard system and overriding of the decisions of the onboard system, if necessary.

Control responsibility for manoeuvres

The second type of responsibility, with one exception, will also remain during the entire rendezvous mission the responsibility of the control centre of each vehicle. This is the safest way of operation. A direct interaction with a spacecraft by a foreign team that does not possess all the detailed knowledge of design and behaviour of the vehicle would always compromise the functional security of the spacecraft. The one exception is the initiation of a stop, retreat or CAM command in the case of immediate danger of collision. Such interactions will therefore be restricted to very simple operations and single commands. If more complex interacting operations are foreseen, as (e.g.) with the remote manual control of the chaser vehicle to ensure mission success (see section 6.5), long and detailed training of the operator will be necessary.

Collision safety responsibility

This will, by nature, involve all participating parties of the mission. Although the onboard system has its own failure detection and CAM initiation function, there may be contingency cases where remote operators in the control centres of the chaser or in the target station can identify a collision danger situation which has not, or not yet, been detected by the onboard system.

The depth of involvement of target ground operators or crew will depend, however, on the phase of the mission, or rather on the time remaining up to a potential collision. As long as this time is relatively large, e.g. at the beginning of a typical half orbit duration manoeuvre, there will be still be time for the chaser ground operators to initiate a stop, retreat or CAM, when a dangerous situation has been detected by the target side. However, when the two spacecraft are at such a distance that collision could be imminent within a few minutes, it will no longer be safe to rely on an initiation of the manoeuvre by the chaser CC after a verbal CAM request by the target CC or crew. Because of the possibilities of communication link failures or operator mistakes it is necessary that, in addition to the chaser onboard system and chaser ground operators, the target ground operators and crew must also have in the last approach phase a direct command capability to stop the approaching chaser vehicle or to remove it from the close vicinity of the space station.

Mission responsibility

All decisions related to the mission have, in principle, to be taken jointly by both control centres. As there will be time restrictions, operation schemes must be set up according to the mission phase, to ensure that decisions can be made between the two control centres within the necessary time. For the nominal case, mission planning has been performed and agreed between the parties long before launch. The most important joint decisions to be made during the mission are the ones for 'go-ahead' at hold points or entry gates. For non-nominal situations, e.g. in case of interruption or delay of the nominal mission, contingency operations and mission re-planning have to be performed. Contingency operations fall under the control responsibilities for manoeuvres and collision safety, discussed above. The formation of a new mission plan may be performed by either of the control centres or jointly; the implementation will inevitably require joint decision making.

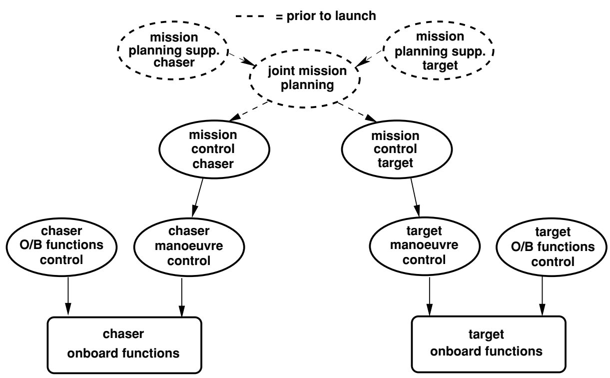

Figure 9.2. Responsibilities of ground control teams prior to the rendezvous phases.

Figures 9.2 and figure 9.3 show how the responsibilities are distributed for mission phases prior to rendezvous and for the final rendezvous phase, respectively. Before entering into the rendezvous phases proper (for a definition of rendezvous phases see figure 2.1), the two control centres can independently control the execution of the mission plan for their own vehicle. In the case of delays or more important contingencies, there is, at this stage of the mission, probably sufficient time available to prepare off-line a new mission plan and agree on it afterwards, while a (possibly pre-planned) contingency manoeuvre plan is executed by the chaser CC. This could be, e.g., a transfer to a higher orbit, gaining time by the slower phasing velocity, or a continuation of the nominal mission up to the first hold point and waiting there.

The situation is different during the rendezvous phases (figure 9.3). Any contingency leading to a delay, mission interruption or a mission abort must be handled in a coordinated manner. These types of contingencies will eventually lead to a loss of synchronisation with communication windows and illumination conditions and will instigate

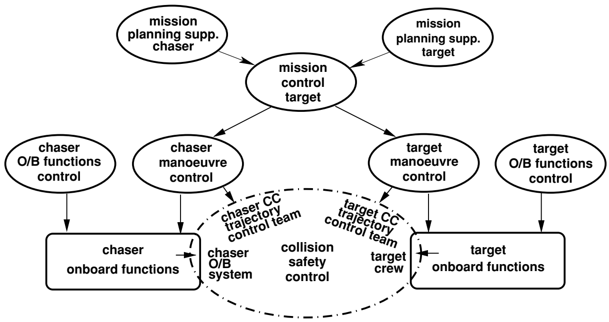

Figure 9.3. Responsibilities of ground control teams during final rendezvous.

re-planning of the approach. In contrast to the pre-rendezvous phases, there is, in the vicinity of the target, not much time available for re-synchronisation. As a result, at this stage any changes in the approach sequence immediately affect the operations planning of both vehicles. For this reason, a hierarchy of authority and rules must be established, which have to be followed in case of contingencies. This will ensure sufficiently fast and coordinated reactions, on either side, to ensure collision safety and to elaborate and implement recovery and mission re-planning. The rules to be followed will depend on the type of trajectory flown and on the distance to the target, i.e. the time left to a potential impact. For example, in the ISS scenario it is a requirement that prior to initiating a chaser trajectory which will enter the 'Approach Ellipsoid' (see section 5.6), mission authority will be transferred to the ISS CC, which at that point becomes the highest control authority for both vehicles.

The hand-over of the mission authority to the target CC at the start of the close range rendezvous operations requires that the target CC receives sufficiently detailed information on the chaser that enables it to make judgements on proper mission progress and on possible collision danger. The necessary information includes the chaser state vector (position, attitude and rates) and general information on health and redundancy status of chaser subsystems involved in the rendezvous process. If, in the case of a contingency, the mission authority decides on a mission hold (stop on straight line trajectory or retreat to a hold point), the mission timeline will have to be re-planned in order to synchronise the approach sequence with communication windows and Sun illumination, and possibly also with the work/sleep schedule of the crew in the target station. As the resources and corresponding infrastructures (e.g. relay satellites, ground links) of two vehicles are involved, re-planning will have to be carried out in cooperation with the mission planning support teams of both control centres. In the case of a CAM, both sides will have to analyse whether and how the remaining resources will allow a recovery strategy and/or a resumption of the mission.

As already mentioned, the chaser and the target may be controlled by two teams in the same control centre, as has been the case in the past in both Russian (Soviet) and

US rendezvous missions. In such cases, the separation of control authorities may be less pronounced. In future scenarios, such as that begun with the ISS, chaser and target vehicles will more often be owned by different powers. This requires a clear definition and separation of control authorities.

9.2 Ground segment monitoring and control functions for RVD

9.2.1 The concept of supervisory control

During the rendezvous phases of a nominal mission, the automatic control system of an unmanned chaser vehicle performs practically all the tasks necessary for the approach up to capture, so the human operator at the ground control centre mainly has to monitor the evolution of the trajectory and attitude of the vehicle and the status of its onboard systems. The term 'human operator' is used here for any member of the control team involved in monitoring and command, in contrast to the automatic operations by the onboard system or to automatic operational functions of the ground segment. In the nominal mission, in addition to the few tasks identified in section 9.1.1, the human operator may have to send to the onboard system an update of the mission timeline, e.g. if there are unexpected minor delays. Such delays may be caused by any reason, not necessarily only by the chaser.

Despite all analysis, design and verification efforts, it will never be possible to create an automatic system which can cover all contingency cases and take into account all possible causes and combinations of external and internal malfunctions and disturbances. Therefore, human operators need, in addition to the tasks identified for the nominal mission, to be able to interact with the onboard system, to command thrust manoeuvres, to change the onboard system configuration and potentially to up-link modified control software. This concept of monitoring and high level interaction in cases where extra intervention is required has been termed 'supervisory control'.

For unmanned vehicles, remote human operators on ground or in the target vehicle can, in the case of contingencies, to a certain extent take over the role of a pilot. In particular, for mission success probability, for which the automatic system usually provides only single failure tolerance, the direct control of the spacecraft motion by human operators may be helpful in rescuing the mission. In contrast to 'supervisory control', this concept is called 'manual control', and has been described already in section 6.5.3.

Whereas in contingency situations the pilots aboard manned vehicles can provide human intelligence to analyse the problems and find solutions, an automatic system can handle only those cases which had been considered already at its design. For automatic vehicles, it is, therefore, essential that the information necessary to analyse potential problems is provided to the human operator on ground. In contingency cases for normal

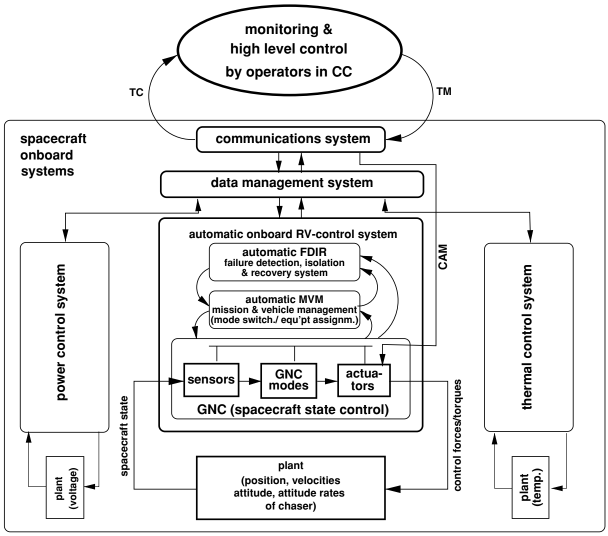

Figure 9.4. Supervisory control of automatic onboard system by ground operators.

satellites with more or less fixed orbits, comparatively large periods of time are available for the ground operator to fix a problem. On the contrary, in a rendezvous mission, the required reaction times are much shorter, ranging from a few seconds up to one half orbit maximum (3/4 h), depending on the trajectory and distance to the target. To perform the tasks of 'supervisory control', operators in the control centres need computerised support tools which facilitate fast recognition of the situation and immediate preparation of the necessary commands for trajectory safety and recovery.

To be aware of the situation, and to be able to analyse and predict the future state, the human operator needs to know the actual status of the vehicle functions and, as much as possible, the individual outputs of equipment and functions. These data must be compared with the planned data for the actual point in the mission timeline. To protect the target vehicle from collision danger, the operator must be able to identify very quickly the danger and provide commands to the chaser vehicle, e.g. for a stop on a straight line trajectory, for a retreat to a safe hold point, or for a CAM. To ensure mission success, the operator must be able, following any delay or change in trajectory sequence, to re-plan the mission and to provide the corresponding commands for manoeuvres, change of timeline and trajectory parameters to the onboard system.

To enable the operator to identify failure causes, the support systems should provide (in addition to the currently transmitted onboard data) detailed information on the nominal (expected) status of equipment and software and on the expected processing results of all subsystems at the time in question. The support systems should also be able to provide information on the effects of typical equipment and software failures.

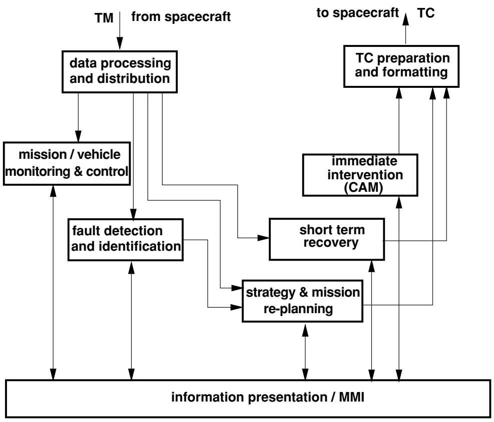

Figure 9.5. Ground operator support functions.

9.2.2 The functions of a support tool for ground operators

The typical functions of a support tool for operators in a control centre are shown in figure 9.5. The telemetry (TM) data received from the spacecraft are processed and distributed to the monitoring functions, to the failure detection and analysis functions and to the re-planning functions. The output of these functions to the operator and the operator's input to these functions are performed via the man–machine interface (MMI), which, in the simplest case could be a normal computer screen and a keyboard. Commands and data sent to the spacecraft need to be formatted, packaged and inserted into the telecommand (TC) data stream.

Monitoring

Monitoring information must contain the state of the vehicle concerning attitude, position and rates (together with the planned values) relating to the actual point in the mission timeline, the present GNC mode, the actual configuration of equipment and functions and the status of the communication links. For this purpose the telemetry data stream from the vehicle must provide update information on the state vector and onboard system conditions at sufficient frequency. The data must be processed and displayed in such a way that the operator can quickly grasp the situation and make appropriate decisions.

To provide the reader with an idea of the ways in which spacecraft data could be displayed, concepts of a trajectory monitoring display and of a system monitoring display are shown in figures 9.6 and 9.7. Similar concepts have been described in Fehse & Ortega (1998); Ortega & Alvarez (1998); Sarlo, Barrera & Ortega (1998); Ortega (1999); and Sarlo, Barrera, Ortega & Franco (1999). As not all information can be displayed on one screen, the basic concept includes a stack of displays, which can be called up by clicking via mouse and cursor on a button or a particular field in the display. This starts

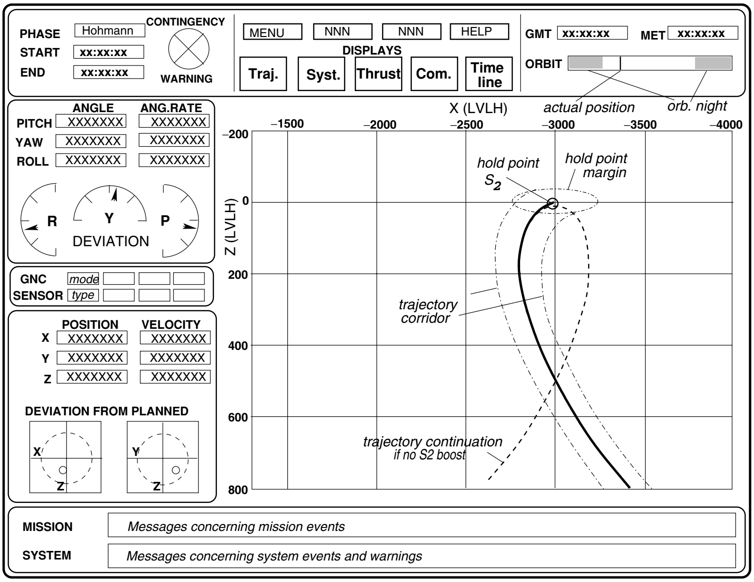

Figure 9.6. Concept of a trajectory monitoring display for ground operator.

the new display indicated by the button or field. For example, in the system display shown in figure 9.7, one could click on one of the fields, such as ‘propulsion system’ or ‘data management system’ to bring up on the screen a more detailed display of that particular function. Fields and buttons for particular functions should be colour coded to indicate the status of that function. Such colour codes could be, e.g.,

green = engaged – healthy
blue = not engaged – healthy
red = engaged – failed
violet = not engaged – failed

There may be top and bottom bars or windows arranged at the sides of the screen, which would be the same for all displays. These common fields for all displays could contain general information on the mission, e.g. on time, mission phase, orbit position, and further messages and warning lights for major contingencies and buttons to switch between major displays. The buttons in the fixed part of the display should be the ones needed by the operator to switch between those displays which are providing a complete high level overview on the status of the mission and of the spacecraft systems. The buttons for switching to the major displays could also be colour coded, indicating the display where the nature of the contingency can be found. In addition, there should be a flashlight in the fixed part of the display, to warn the operator in the event of critical contingencies, whatever display is switched on. Such critical contingencies could be the interruption of communications between chaser and target for longer than a specified duration, the transgression of safe limits for state vector components (position, attitude, rates), unrecoverable thruster failures, loss of last redundancy level for critical equipment, etc.

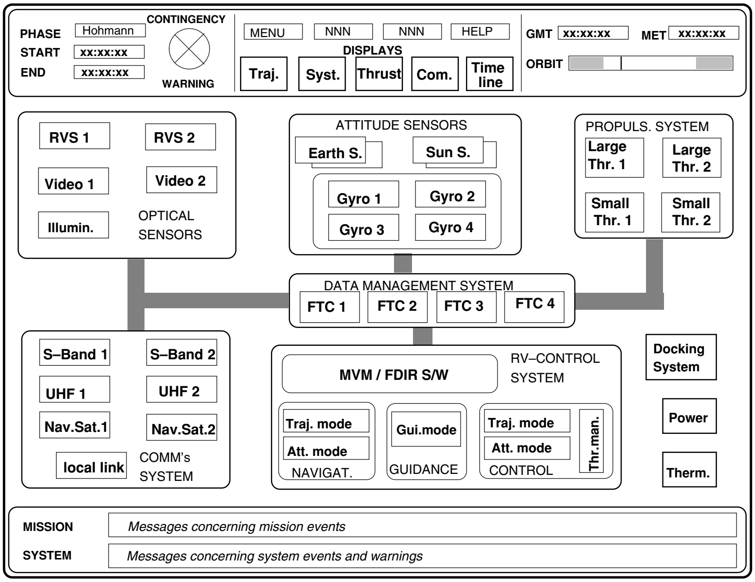

Figure 9.7. Concept of a system monitoring display for ground operator.

For the last few tens of metres of the approach up to contact, a display of a video picture of the opposite vehicle together with the relevant system information, as shown in the crew operator display, figure 9.8, would also be useful for the ground operator. This requires, however, the availability during this period of a downlink with the capability of transmitting video data (cf. table 9.1). This is not available with the normal links used for TM/TC transmission. In the Russian space programme, a chain of ground stations has been set up for this purpose, as shown in figure 5.20, from where the video information is transmitted to the control centre. In this case both the following synchronisation requirements have to be fulfilled: the last metres of approach and docking must take place at proper illumination conditions and when the vehicles pass over the dedicated ground stations.

Immediate intervention

In this function, pre-programmed commands or command sequences are stored, which can immediately be called up by the operator and sent via the TC formatting function to the spacecraft. Pre-programmed commands will be used in the nominal case for, e.g., the ‘go-ahead’ commands after hold points. In contingency situations they are used for commands to stop motion on V-bar or to initiate a CAM. As the CAM may be different for each approach phase in terms of ΔV and thrust direction, the pre-programmed CAM command must be linked to the current approach phase. Also, a command for a stop on V-bar must be inhibited for all approach trajectories which do not follow a straight line V-bar approach. For safety-critical operations, such as the command of a CAM or of an immediate stop on V-bar, the input may be given via a separate protected button, hard-wired to the ‘TC send’ function.

Short term recovery

Procedures for manoeuvre sequences are stored in this function. These procedures are not fixed single commands or fixed command sequences, but require, for each point on a trajectory where a contingency happens, a new calculation of the starting time for the next thrust manoeuvre, or of the ΔV to be applied, or both. Also, different GNC modes and altered sequences of trajectories and attitudes can be stored in this function, e.g. to retreat from points on the nominal approach trajectory to the previous hold point.

These are all short term manoeuvres to be followed in cases of limited mission interruptions or delays, i.e. where the subsequently resumed approach follows the nominal sequence. In this case, the control software does not need to be changed and, for the resumed approach, only the timeline has to be updated such that it is re-synchronised with external events such as Sun illumination, communication windows, etc. Recovery of the nominal approach sequence may take place, e.g., after hold on V-bar, after return to a previous hold point or after retreat to a safe waiting point on V-bar. Opportunities for re-synchronisation may occur immediately in the next few orbits or otherwise after about 24 hours.

Mission re-planning

This function is required to ensure mission success after large deviations from the nominal trajectory or timeline. For instance, after a CAM, the position and velocities of the chaser vehicle would be so far away from the nominal state that a complex sequence of manoeuvres needs to be performed to return to a position from where the nominal automatic approach sequence can be re-initiated. As the amount of time and propellant required for recovery would rapidly increase with the duration of the contingency, a recovery strategy would need to be worked out, and the manoeuvres would have to be defined quickly. The function will, therefore, have to include a fast computer for strategy re-planning and a high fidelity orbit dynamics and environment simulator to verify the recovery mission plan.

Failure detection and identification

This function must permit the operator to arrive quickly at an assessment of the nature and severity of the failure. If possible, the operator should also identify the cause of the failure, in order to be able to judge the potential long term repercussions. Failure identification will begin with a general indication that a function or equipment has malfunctioned or that a parameter is outside the nominal margins. Failure identification can be supported by computer programs, which, e.g., can compare the actual values received from the onboard system with the nominal ones, obtained by support equipment in real time or by analysis prior to the mission. For fast identification of detailed causes of hardware and software malfunctions, so-called 'expert systems', i.e. knowledge based search programs, may be developed. For the constraints in transmitting onboard data to ground, see section 9.3.2.

It is obvious that the above description of functions can indicate only basic requirements and concepts. There are many ways of implementating the functions, and, as in the case of many other functions, the accumulated experience with available equipment and procedures may be the decisive factor for the actual implementation. Where the same parameters have to be monitored in the same mission by two different control centres for the close range rendezvous phases, a certain standardisation would be advantageous. A standardisation of essential display features would facilitate the communication between the control centres concerning the assessment of the particular situation when decisions become time-critical.

9.2.3 Monitoring and control functions for the target crew

As discussed above, in the close vicinity of the target, the crew aboard the target station must also be able to monitor the chaser's deviations from the planned state vector evolution, the status of the chaser's equipment essential for the control of the approach and the status of the communication links. The crew operator must further be able to command a stop, a retreat or a CAM, if the situation makes immediate action necessary and if there is no time available for the involvement of the ground operators. This requirement means that the crew should have available support tools similar to those in the charge of the ground operators. It will not be necessary, however, for the crew support tools to contain the more complex analysis and re-planning functions that are required for the support of the ground operators. Monitor display designs for crew operators in a space station need to be compatible with the computer screens available aboard the vehicle. In the past, television type cathode ray tubes (CRT) have been used in the Russian (Soviet) and American space programmes. The amount of graphic detail and text which could be displayed on such screens, however, was limited. On the laptop computer screens available to the crew in the ISS, probably less detail can be displayed than on a large computer screen on ground. In addition, on ground there will be a team of several people available for monitoring and control of the various parameters and features, whereas in orbit there is probably only one crew member available for this task.

The most important monitoring tool for the crew operator will be a monitoring display showing the relative state of the chaser vehicle w.r.t. the target. When the chaser is at a distance where only sensor information is available, this display can be designed to be similar to the trajectory display for the ground operators (see figure 9.6). In the close vicinity of the target, when the approach is additionally monitored by a video camera, a different type of display may be used, which would then include the video information. As it is advisable that the operator in the target station can concentrate during the most critical part of the approach on one single screen, it is preferable that trajectory and RV-control system information is superimposed on the video picture.

Such a system was developed in Russia to monitor the Soyuz and Progress rendezvous operations with the Mir Space Station. The system used analogue (television) techniques for video display, which included alphanumeric information on the relative state vector. At the time of writing, this system was still in use on the Russian part of the ISS.

A modern concept for such a display, integrating a digital video picture with control system information on a LCD computer screen, is shown in figure 9.8. A similar display has been shown in Sarlo *et al.* (1999). It is assumed here that the video camera is located on the chaser vehicle. In a $-$V-bar approach, this arrangement has (a) the advantage of better Sun illumination conditions at the end of the approach, and (b) provides the same view as a pilot in the chaser vehicle would have. On the target vehicle a visual target pattern of the type shown in figure 6.23 is assumed to be mounted in a position opposite to the camera when docked. If the chaser is on the nominal approach line with the correct relative attitude to the target, this target pattern would be in the centre of the image. Fixed grids would enable the operator to make judgements about linear and angular misalignments of the chaser vehicle during approach. In addition, position, velocities, attitude and angular rates could be displayed in alphanumeric form. Translational accelerations and angular rates could be displayed as arrows, which would enable the operator to assess the trend of trajectory and attitude development.

Flashing lights could warn the operator, e.g., about contingency situations in the automatic system and about critical link interruptions. For the chaser–target–chaser link the target operator has the main monitoring responsibility. Function buttons on the main monitoring screen would enable the operator to switch over to other displays, such as the trajectory display, the system display or (after contact) to the docking system display. In addition to the information on the chaser, some essential information on the status of the target system could be provided on a dedicated status display. Colour coding of the switch buttons could, as in the case of the ground operator tools, provide additional information on the type of contingency and could indicate where to look for more detailed information.

The onboard operator will also need a minimum of command capability for collision safety control, as discussed in section 9.1.2. Such commands may be:

- thrust inhibit,
- stop on V-bar,
- CAM.

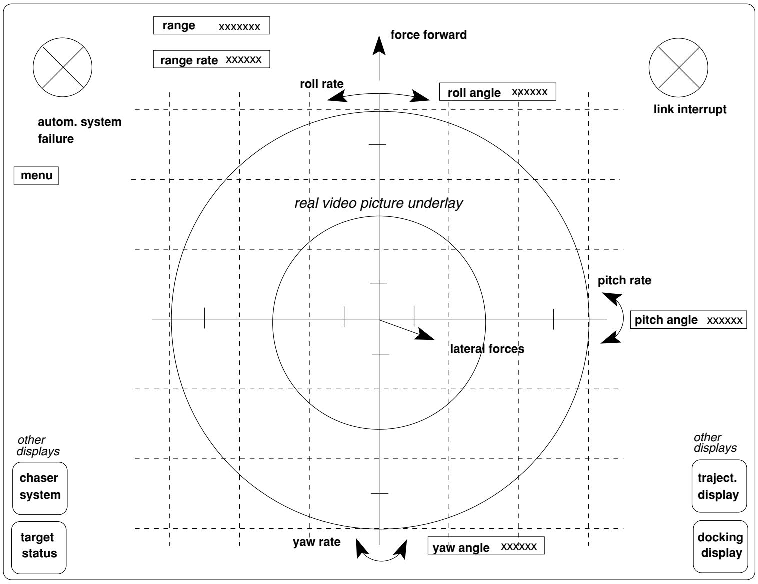

Figure 9.8. Concept of a final approach monitoring display for the target crew.

The available commands will depend on the stage of the approach, as the first two commands make sense only for particular trajectories and distances from the target. For instance, 'thrust inhibit' may not be of much use on two-pulse transfers, where the trajectory just naturally continues. Depending on the approach velocity, thrust inhibits may even be dangerous in the last part of a V-bar approach. A 'thrust inhibit' command would be a useful remedy in the first part of V-bar and R-bar straight line trajectory, when the resulting trajectory is collision safe (see section 4.4.2). The 'stop on V-bar' command must be inhibited for all guidance modes except 'straight line V-bar trajectory'. The 'stop on V-bar' command requires that the chaser RV-control system is fully functional, as after reception of the command the onboard system has to engage automatically a deceleration mode and subsequently a position keeping mode.

The command interfaces for an operator in the target station will probably be just one or two physical buttons, hardwired to the communication function. These buttons, particularly the one for the CAM, will have to be specially protected to avoid inadvertent activation. In the nominal approach case there will be no interaction between the target crew and the chaser vehicle.

Manual control of the chaser by a target operator as a backup for mission recovery has been addressed already in section 6.5.3. The command interfaces for this case could consist, e.g., of two joysticks, where one is for the control of the three translational DOF and the other one for the three rotational DOF. This is the concept for manual control of the unmanned Progress vehicles implemented in the Mir and ISS scenarios.

9.3 Communication constraints

The purpose of this section is to give a short overview of the repercussion of communication constraints on the automatic rendezvous operations and on the monitoring and control by remote human operators. It is not the intention of this chapter to cover space communication systems and structures. Detailed information on these subjects can be found in, e.g., Morga & Gordon (1989) & Wertz & Larson (1991).

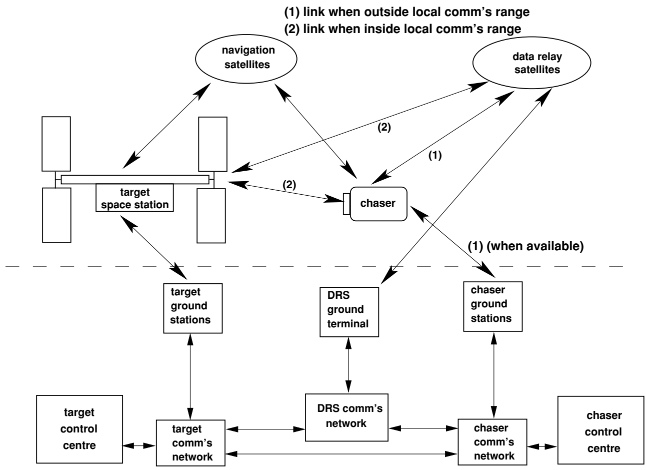

Figure 9.9. Overall communication scenario for a rendezvous mission.

A typical communications scenario for a rendezvous mission is shown in figure 9.9. Both vehicles communicate with their respective control centre via data relay satellites and, when available and if planned, via dedicated ground stations. In the rendezvous phases, when local communications and relative navigation have started, the information on the state vectors of both chaser and target must be available in both control centres and, during the very last part of the approach, also to the station crew. For this reason, communications may be routed via one of the two spacecraft, usually the target station, and the combined data stream will be distributed to the control centres. In the case of relative navigation using navigation satellites, a communication link between chaser and target needs to be available anyway (see section 7.3.3). The ground communication networks of chaser, target and relay satellites will use both dedicated lines and commercial ones, rented during the mission from local telecom organisations. The latter possibility has to be considered in particular for links with ground stations that are located in remote parts of the world, but is potentially used also for some of the other ground links. Whichever link is used, the space ground data stream will pass on its way from the spacecraft to the ground control centre, or vice versa, through many receivers, amplifiers and computers, potentially adding noise and delays. The major issues and constraints associated with the communications links in a rendezvous mission are as follows.

- Communication windows: the point in time and duration for which data exchange between space and ground is possible.
- Availability and reliability of the links: the probability of deteriorations, interruptions or losses of the link and the corresponding loss of data.
- Constraints of the communication link due to bandwidth or data rate limitations: the capability of transmitting a certain amount of data per unit of time.

The first issue has been discussed already in section 5.4.2; the most important aspects of the two other issues are discussed below.

9.3.1 Data transfer reliability

Considering that the link budget is designed, under normal conditions, to provide sufficient margin for the sender–receiver distance, link deteriorations or interruptions can be causes by:

(1) equipment failure of communications equipment in the spacecraft, on the ground station and in the intermediate link constituents such as relay satellites, telephone lines, etc.;

(2) too low signal-to-noise ratio of the received signal due to (i) attenuation by atmosphere, e.g. at low elevation angles of the antenna LOS and by rain, due to (ii) attitude changes of the spacecraft, reducing the antenna gain, and to (iii) shadowing by structural elements of the spacecraft or by the other vehicle etc.;

(3) disturbances of the received signal by other radio sources sending on the same frequency and by multi-path effects.

Communication equipment (receivers, amplifiers, etc.) both on spacecraft and in the ground station can be made redundant. This is, however, generally not possible for the complete link. The radio link between the antennas of the spacecraft and the ground station, the links to and from the relay satellites, and the telephone lines on ground are generally not redundant. Except for the very limited possibility of parallel communication, e.g. (a) directly with a ground station and (b) via a relay satellite, there is no complete redundancy in ground–space communications. When considering the collision safety control aspects during the last part of the approach, the fact that that communication links are prone to failures is of particular importance.

There are systematic and random link interruptions. The systematic ones, e.g. those due to coverage by ground station and relay satellite, can be well predicted and taken into account during the mission planning. Random interruptions, e.g. those due to atmospheric disturbances and other causes (see points (1)–(3) above) can be predicted only with a certain statistical probability. The duration of such interruptions will always remain uncertain. Typical data on length and frequency of occurrence of such interruptions can, however, be determined empirically in a scenario with frequent rendezvous missions, such as the Mir or ISS scenarios.

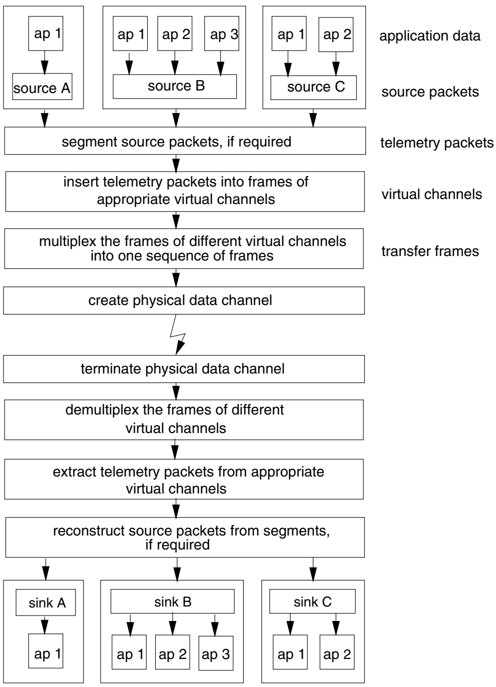

Figure 9.10. Packet telemetry data flow (after CCSDS 1987 a,b).

Because of the potential disturbances and interruptions, all communication between the spacecraft and ground, i.e. both the telemetry (TM) and the telecommand (TC) streams, need to be protected by encoding, to facilitate the checking of the integrity of received data. For this purpose, standards for packet telemetry and packet command streams have been developed, which are today used by most spacecraft (CCSDS, 1987 a,b). Figure 9.10 shows the various steps of encoding and decoding of a packetised TM-stream with application data from various sources of the spacecraft, i.e. spacecraft subsystems and payload.

The packet TM transmission protocol ensures that corrupted packets will not be used in the decoded application data and that an error message is issued when a package has not been received. A segmentation process permits the breaking up of very long source packages into shorter pieces to fit them into the data flow. By assigning each group of sources to a dedicated sequence of transfer frames, virtual channels are created in accordance with the frequency requirements of the source data. The frames of the different channels will be inserted into a sequence of frames, which is the data stream transmitted to ground.

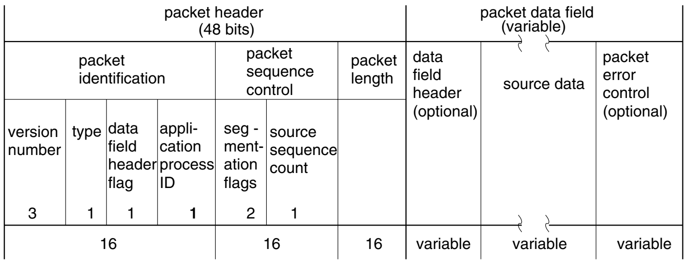

Figure 9.11. Format of a source packet (after CCSDS 1987 a,b).

The format of a source packet, figure 9.11, is the one described in CCSDS (1987b) as ‘version 1’ format. It is the firstlevel of encoding identified in figure 9.10. The source packet has a header, which includes identification, sequence control and length, and a data field, which can be arranged according to the needs of the source applications. Similar codes in headers and trailers will be added at each further step of encoding shown in figure 9.10. As most space communication systems are capacity-limited, the penalty to be paid for this reliability improvement mechanism is a reduction of transmittable data rate for the applications. To send the data flow from the transmitter to the receiver antenna, so-called ‘channel coding’ is applied, which has the effect that distinct messages are clearly distinguishable from others (CCSDS 1997). In combination with data compression techniques, ‘channel coding’ achieves transmission of higher bit rates at lower bit error rates.

Packet TC transmission is implemented in a similar way. In addition to the first measure, which concerns the completeness of the shell of the information package, the proper receipt of the information contents can be ensured by additional measures, e.g. the acknowledgment of TC by the onboard system.

9.3.2 Data transmission constraints

In addition to interruptions and distortions, the constraints for the data transmission between the ground and space segment during a mission are:

- the planned availability of the links,
- the delays with which the data arrive at their destination,
- the data rate or frequency bandwidth which can be transmitted.

Planned availability of links

Many of the ground links and the links via relay and communication satellites will be rented from other authorities (including commercial ones) for the time of the mission. Contingency situations causing approach delays will have to be taken into account in the planning of the availability time. For cost reasons it may, however, not be possible to cover all possible contingencies by a fixed duration of the planned link availability. This is true particularly for TV channels, if docking under video monitoring by ground is planned. As the recovery from a CAM (e.g.) may take one or more days, possibilities must be planned to re-open such an expensive link when required.

Communication delays: space–ground, ground–ground

Due to the altitude of the relay satellites (36 000 km), the two-way communication delay is 0.24 s. To this amount must be added the receiver–transmitter delays of the spacecraft (in the case of transmission from the chaser via the target, of both spacecrafts) and of the relay satellite as well as the delays due to the ground links. Because of the multitude of amplifiers and computers in the ground links and of the possibility of additional ground–space hops via communications satellites between the ground station (antenna) and the ground control centre, the total round-trip time may take a couple of seconds. This has to be taken into account in the timing of manoeuvre commands and in the evaluation of TM data. Solutions to this problem include the application of time tagging for manoeuvre execution and of time markers for TM, e.g. to identify the correct time relation of GNC data.

Communication data rates: space–space, space–ground

There are usually limitations of data flow between space and ground due to the data rate capacity of the link. As we have seen in the previous section, not all the total data rate of a link is available for transmission of user data, but in the case of encoding in packages a part of it will be needed for securing the integrity of the data transmitted. Because of the multiple encoding process shown in figure 9.10, a significant amount of overhead will be added to the source data in packet TM, which can be more than 10% of the total data rate, depending on the type of application and mission.

The data rate is defined as the number of samples per second times the number of bits per sample. For analogue signals the Nyquist theorem requires that the sampling frequency must be at least twice the highest frequency of the signal spectrum to be transmitted:

$$f_{\text{sample}} > 2f_{\text{signal}}$$

In practice, because of filter limitations, a factor of 2.2 rather than 2 will be applied (Wertz & Larson 1991) for data transmission. For digital data transmission, the quantisation error must also be considered. The maximum quantisation error decreases from

Table 9.1. Bit rate required to transmit analogue information (after Wertz & Wiley 1991).

Analogue type of data	Max. input frequency f_{m} (Hz)	Sampling frequency (samples/s)	Number of bits per sample	Data rate R (bits/s)
Voice (PCM)	3600	8000	7	64×10^3
Voice (delta PCM)	3600	8000	6	56×10^3
Colour television (commercial quality)	4.0×10^6	8.8×10^6	5	44×10^6
Colour television	4.2×10^6	9.25×10^6	10	92.5×10^6

6.25% at 3 bits/sample to 1.56% at 5 bits/sample and to 0.05% at 10 bits/sample. The required bandwidth of the link will depend also on the required quality of the signal to be received. Table 9.1 gives examples of bit rates required for certain types of analogue input data. Data rates concerning television refer to US standards.

Typical TM/TC data rates required for the operation of satellites are in the range of a few tens of kilobits per second, comparable to voice channels, whereas the TM requirements of the payload will vary depending on the mission and can assume values of a few hundreds of megabits per second. A significantly higher TM data rate than for conventional satellite missions will be required for rendezvous missions, since guidance, navigation and control data for six DOF motions and information on the operations of the automatic system have to be transmitted comparatively frequently. In the example shown in figure 9.12, the total amount of information pertaining to the onboard RVC system which could be transmitted to ground is 9184 bytes or 73 472 bits. If this amount of data had to be transmitted once per second, it would exceed the capacity of a voice link. Of course, not all variables and parameters are changing or required with that frequency on ground. It could be that only a part of the information is needed at lower frequencies, at certain intervals, or only in particular situations, so that the actual data rate of this source can be significantly reduced to fit into the capacity (some tens of kilobits per second) of links for spacecraft operation. If video transmission is required during the last few metres of approach and contact, the downlink requirements increase significantly (see table 9.1). With modern compression techniques, however, the bit rate requirements can be reduced by large factors, and, due to the low velocity of approach, the number of frames per second can be reduced to values of 10 or less without significant loss of information.

Communication frequencies

Frequencies available for space operations are a scarce commodity which has to be shared by many users. With the development of radio-transmission applications, more

Table 9.2. Frequency bands used in non-commercial space applications.

Band	Frequency range	Frequency type	Use for space
	30–225 MHz	VHF	∼137 MHz (up), ∼149 MHz (down) ∼270 MHz (down)
	225–1000 MHz	UHF	400.15–401 MHz (proximity links) ∼450 MHz (up)
L-band	1.0–2.0 GHz	UHF	∼ 1.5–∼ 1.7 GHz
S-band	2.0–4.0 GHz	UHF	∼2.1GHz (up), ∼2.3 GHz (down)
C-band	4.0–8.0 GHz	SHF	∼7.2 GHz (up)
X-band	8.0–12.4 GHz	SHF	∼8.5 GHz (down)
Ku-band	12.4–18.0 GHz	SHF	13.23–15.35 GHz, (13.4–14.0 TDRSS)
K-band	18.0–26.5 GHz	EHF	16.6–17.1 GHz (down) 22.55–23.55, 25.25–27.5 GHz (DRS) ∼26 GHz (proximity, & multipoint)
Ka-band	26.5–40.0 GHz	EHF	∼32 GHz (down), ∼34 GHz (up) 37–38 GHz (lunar, planetary-down)
Q-band	40.0–60.0 GHZ	EHF	40–40.5 GHz (lunar, planetary-up)
V-band	60.0–75.0 GHz	EHF	∼65 GHz (no direction specified)
W-band	75.0–110.0 GHz	EHF	

and more frequency bands will be firmly occupied for fixed services on ground and in space. Frequency bands for any type of applications are assigned by the International Telecommunication Union (ITU), an intergovernmental body comprising representatives from the majority of countries in the world. Recommendations concerning frequencies and data formats for space applications are provided to the ITU by organisations such as the Space Frequency Coordination Group (SFCG) and the Consultative Committee for Space Data Systems (CCSDS). The frequency bands for space operations shown in table 9.2 allocated by the World Administrative Radio Conference, Geneva, are extracted from documents produced by these organisations (CCSDS, 1997). As the utilisation of radio-frequencies will evolve further in the future, re-allocation of frequencies may become necessary, and the bands available for space operations may change.

The available bands in the 2, 7 and 8 GHz regions are subdivided into channels of 100 kHz. If commercial telephone lines are used for transmission from ground stations to the control centre, the data rate limitations of these lines have to be taken into account too, e.g. 56 kbits/s for ISDN lines. Bandwidth requirements of 10 MHz and more are already now increasingly difficult to satisfy in the frequency bands for space application below 10 GHz. Frequencies above 15 GHz are, at the time of writing, less crowded. For video data transmission between the spacecraft, the 26 GHz band is suitable. Video transmission to ground can be done, e.g., via TDRSS in the 14 MHz band, in which case a wide-band channel has to be rented for the planned transmission time. Otherwise, for direct transmission to ground stations (for communication window constraints see section 5.4.2), channels in other high frequency bands may have to be requested.

Since the capacity of the link available for user data transmission will have to be shared by the TM data from all the spacecraft subsystems and payloads, there will, for each of the subsystems, be only a very limited data rate available. In a rendezvous mission, payload data do not need to be transmitted, and the most important spacecraft subsystems are of course the GNC and propulsion systems. Nevertheless, in most cases the data rate available does not allow the transmission of all onboard data which would be of interest to the ground operator.

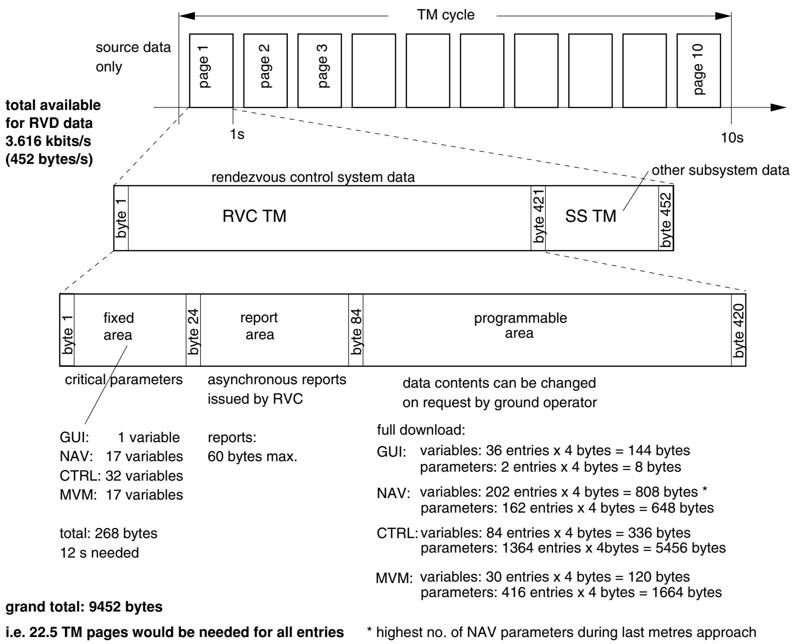

Figure 9.12. Typical GNC telemetry (TM) data transmission for a rendezvous mission.

Telemetry message format

An example of severe link limitations in the transmission of chaser onboard data is shown in figure 9.12. The availability of only 3.6 kbits/s = 452 bytes/s is assumed for the entire amount of RV-control data plus the necessary amounts of bytes for the packet header and error control. As the total amount of GNC and MVM data in this example is 9183 bytes (more than the entire capacity of a voice link), this will allow the transmission of a system overview, but no details. A possible solution to this problem could be the creation of fixed and programmable areas in the TM-message format, where the contents of programmable area can be changed by request of the ground operator. If the data in the fixed area of the message indicate a problem in one of the functions guidance (GUI), navigation (NAV), control (CTRL) or mission and vehicle management (MVM), the ground operator can send a TC to the vehicle to change the content of the programmable area such that it obtains more detailed information on the particular function in trouble.

The problem with this arrangement is the amount of time necessary to obtain more detailed information. Another problem in this example is that the fixed data for GUI, NAV, CTRL and MVM alone have a total volume of 268 bytes = 2.14 kilobits/s, which is about 60% of the total data rate available for GNC and MVM. To have a reasonable capacity available for the programmable area, the fixed area has been limited to 23 bytes. The refreshment of all data in the fixed area would, therefore, take about 12 s.

With the target S/C (space station) acting as communications relay, additional constraints may have to be observed during proximity operations. The advantage of this arrangement is that all information which the chaser transmits to ground is automatically available also on the target spacecraft. The disadvantage is that the chaser data flow must share the total available bandwidth with the target data flow. As a result, data rate limitations as assumed in the above example can occur.

For the space–space communication link, the range which can be achieved depends on the transmitter power, the antenna areas and the frequency used, as shown in Eqs. (7.12) and (7.25). With the 400 MHz band allocated for proximity links, at reasonable transmission power only limited ranges can be achieved. The 26 GHz band offers capabilities for larger ranges.