issues were not solved only on the base of technical considerations, but other aspects like available components (hardware and software), available expertise, schedule needs, expectations, conflicts with other projects, and many more played a relevant role.

This project is an example of how modern technology has to be combined with work organization and coordination to bring the desired results. A facility of the type here described operates smoothly only thanks to the large work at its base and that is available in form of document support for all types of operations, continuous access to maintenance personnel, etc.

Satellite control is an atypical example to transfer the related experiences to other fields without qualifications. One of the lessons that can be of general interest is that smooth operations depend on the amount of prior planning with consideration to the operational requirements. Even in potentially dangerous situations the controllers have to follow predetermined guidelines; here nothing has to *depend* on improvisation. In relation to the hardware, system availability is ensured by providing redundancy for all equipment, so that spares can always be connected in case of failures.

The user interface was designed in accordance with the operational requirements. An explicit effort was necessary to organise and structure the raw data and make it manageable. The monitoring and control system provides a notable reduction in the complexity of the ground station operations, because it reduces a large amount of data to basic parameters related to describe full systems and the way they work. The use of a monitoring and control system to display the original data on a one-by-one basis, without their previous organization, would have made the control tasks more difficult.

The design of this ground station was evaluated *a posteriori* according to the theoretical frame presented in this work. In most points, the design was found to be in accordance with cognitive requirements and basic principles. This is indirectly a support for the notion that the design of user interfaces may *gain* a lot from theoretical knowledge, but does not fully *depend* on it. Common sense and close scrutiny by the involved parties - in particular the final user - are also important components in the preparation of the user interface for a complex system.

The satellite controllers did not participate in this preliminary phase. DBP Telekom was represented by the group supervisors and project engineers.

IMPLEMENTATION

Some problems were caused by the utilization of a satellite telemetry processor to process also the ground station data. The initial reason was that available processing software and networking equipment could be used right away, In course of time, however, many problems appeared, due mainly to the fact that the application software could not process derived variables properly and some changes in the basic system were necessary.

A new user interface, the Graphical System Manager, has been recently installed on the top of the real-time system, with mixed results. This interface supports the selection of graphical screen pages with the "point-and-click" method, and by zooming in on the desired object. With the current computer configuration, it may lead to system overload when several other tasks have to be active at the same time.

For the purpose of ground station monitoring and control, a general-purpose process data base connected with a graphical editor and a user interface tool (possibly based on a windowing system) could have been an alternative. The development work could have been carried out in a prototyping fashion with the direct involvement of the customer (DBP Telekom) and of the operators.

5.6 Conclusions

The satellite control station in Usingen has been operative since 1989 and has so far satisfactorily fulfilled its purpose. At the moment, four satellites are controlled autonomously and with reduced manpower. Thanks to the modern design of this station, DBP Telekom is able to manage satellite control without resorting to the complex structures and reliance on external organisations that would otherwise have been necessary.

In this chapter were discussed the technical issues related to the design of the user interface at the ground station. As it is inevitable in all large projects, some of the performed with simple commands. For more detailed failure search, the hardware-oriented representations are adequate.

Coding

The monitoring data is presented in a compact form where non-nominal states are immediately recognisable. In case of failure, the related systems are shown in colours different from green and disconnected groups are displayed with framed symbols instead of filled. The operators can visualise the function of the whole station with a glance at a screen.

Complexity of the representation

It was not evaluated as such, but in general all screen layouts are readable with no difficulty. All layouts are structured and balanced.

Operator commands

For routine operations, the control of the ground station equipment takes place with help of command strings, "macros" (Section 5.4). The configuration of single parameters in the devices is possible via dedicated screens, this is however not necessary in normal operations. It is mainly used for maintenance and servicing purposes.

USER PARTICIPATION IN THE DESIGN PHASE; PROTOTYPING

Engineers from DBP Telekom and from Dornier Systems checked all data processing design documents before these were released for the software implementation, and in this phase they presented many comments. All comments were considered, either by inclusion in the design documents or with motivated explanations in support of different design decisions. All parts had to give final approval to the design documents before implementation could begin.

A practical problem arose here because different parts of the specification documents were evaluated by different people. Many of the comments were related to the choice of the names. People advancing alternative proposals for naming were not aware of the requirements for consistency with the names of other devices. At the end, all participants agreed on the proposed design principles and device naming.

high-level variables would have been much more difficult. Both methods were important, each in its specific scope.

INTERFACE DESIGN

Interface matching

Due to the fact that all communication between operators and technical system takes place via computers, there is no intrinsic mismatch between task and cognitive capabilities.

Basic design principles

The principles of visibility, simplicity, and consistency were not explicitly identified as such during the design of the user interface; they could therefore not be applied directly as guiding paradigms for the preparation of the design documents. Common sense and group discussions led anyway often to similar results.

Use of language

Simplicity and consistency were applied in the selection of names for the device parameters.

The use of an older software package for telemetry and telecommand led to some petty problems concerning the use of language. One such problem was that names for parameters could only be 14 characters long. This led to some minor inconsistencies in parameter naming, where some forms and acronyms that would have been dictated by the need for consistency could not be used because of the limited number of characters at disposal.

Process layouts

The aspect of display layouts was described in Section 5.4. The layouts were oriented in first hand to the system hardware. Without an explicit task analysis, the layouts could not be designed to directly support system operations. This fact has however no negative consequences on the way operations are conducted, because the general system page (Figure 5.6) reports all information that is needed for the basic control of the ground station. Emergency operations are used for representing the monitored parameters on a one-to-one display by using the new names).

This type of complexity reduction alone would still not be sufficient to allow the control of the ground station in compliance with the strict requirements for immediate action in case of equipment failure.

Complexity reduction via the monitoring and control system

The most important reduction in the operational complexity of the system is due to the consideration of its function. A very large number of different configurations can be programmed if every parameter is considered on its own, but only a few dozens combinations are actually relevant for operations.

The raw monitoring data is logically connected in aggregate parameters for the description of subsystems and systems. The method for the connection and evaluation of derived parameters at higher levels described in Section 5.4 is used without exceptions for all the raw data. All information needed to evaluate the functional state of the ground station equipment and the indication of alternate paths in case of failure are reported on a general screen (Figure 5.6). The coding method was conceived to support the immediate identification of all non-nominal states. The general representation and the screen presentation also respect the principles of simplicity, visibility, and consistency. There is only one aspect, the number of hierarchical levels, that in retrospective does not seem to be justified; three levels would have been sufficient.

A similar reduction in complexity is realized in the control. The setup of a whole transmission or reception path requires the configuration of a couple of dozens of parameters. But in practical operations, a setup or a new configuration is executed with a single command. The number of the predefined - and allowed - operational configurations is about 40; the name of the commands follows a simple convention and can be memorised without problems (Section 5.4).

The complexity reduction achieved with help of data structuring was the precondition for complexity reduction via derived variables to describe subsystems and systems. Without the preliminary organization of data and introduction of a common representation structure, the definition of the derived

COMPLEXITY ANALYSIS

Complexity of the satellite ground control station

The satellite ground control station is a complex system. It is composed of about 100 devices, delivers 1500 monitoring values and about 350 states can be remotely controlled.

Equipment redundancies and the design structure make the station simpler than it seems. Many devices are similar (transmitters, receivers, etc.), so that when the function or operation of a device is known, it is valid for all other similar devices. In addition, there are no "hidden" or internal states in the devices that have to be inferred by knowledge of the monitored parameters. With few exceptions, the monitored parameters represent the state of the device electronics.

On the other hand, there are factors that increase the complexity of the ground station. The devices are delivered by different manufacturers, and very often different names are used to indicate the same thing. A one-to-one monitoring display based on the original naming conventions by each manufacturer would add considerable confusion to the use of the system as a whole. The sheer amount of data would make the localisation of failures a difficult task. A signal loss in a device would immediately trigger warnings from several other devices along the same path, and it would be difficult to identify the failure source in a short time by analysing all the data. As described in Section 5.4, many warnings make sense only if they are considered in a wider context. The interpretation of the raw data would require a lot of dedicated attention by a person. This would not comply with the operational requirements.

Complexity reduction via structuring

A first reduction in the complexity of the ground station system was achieved with the introduction of a common naming convention and of the general representation for monitoring. Every device, subsystem, and system is described by a similar set of parameters with consistent naming (Section 5.4). This approach complies at the same time with the principles of visibility, simplicity, and consistency. The general representation is independent of the use of the monitoring and control interface (it could indicate how to label the devices, or be remote control, there is a difference between the newer DFS and the older-type TV-SAT. On TV-SAT, all commands are immediately executed if their syntax is correct and no parameter limits are exceeded. In DFS, a command is first loaded in a buffer, and then the state of the buffer is radiated back to earth. The controllers can double-check that the commands were loaded as intended, and after that send an explicit "execute" command.

Most satellite commands do not endanger any system and to override them is sufficient a new command; the controllers do not need to be on constant alert. However, some satellite manoeuvres must be carried out with particular care (e.g. those involving orbit correction). The worst-case error is a change in the orbital orientation or position of the spacecraft, which may have serious consequences (the procedures to "recuperate" the satellite may take days or weeks). The controllers are aware of this fact and take special care in these operations. But in any case, a chain of several fault events - all with a very small probability to happen - must take place before a satellite is endangered.

If something very serious happens with a satellite, all the systems onboard switch off automatically and the satellite starts monitoring a special frequency. A different, and more specialised, control centre would take over the responsibility to reactivate, and if necessary to reposition the satellite. The main consideration concerning the operators is therefore not whether they can do something potentially destructive, but rather that operations have to proceed as smoothly as possible, with no unmotivated disruption of service.

In Section 3.7 was indicated how the system simulation can serve as an important decisional support. At the ground station a very advanced spacecraft simulator for TV-SAT and DFS is installed. This simulator is built partly in software and partly with hardware equipment identical to that installed on the spacecraft. All command sequences prepared by the subsystem engineers can therefore be tested on earth under very realistic conditions before being scheduled for execution. After having been tested, the operational command sequences are included in the station operation handbooks and are available as computer files for immediate loading and execution.

to initiate. In case the failure remains, a system engineer has to be contacted immediately (satellite subsystem engineers are "on-call" on a 24 hours basis).

Alarm states are reported in several ways: by a change of colour on the screen displays, with an online alarm indication on a dedicated log screen, and acoustically; all alarms are also logged on computer files. The operators do not need to watch the screens all the time to detect irregular states.

Mental models

The issue of mental models was - although not explicitly - one major consideration in the operational requirements. In order to carry out routine operations with help of comparatively unskilled personnel, the type of knowledge required had to be strictly operational and not conceptual. The satellite controllers must strictly follow the handbook guidelines. For this reason, the requirements on quality and precision of handbooks and documentation in general were high. On the other hand, it is expected that the satellite controllers become more knowledgeable about the systems in course of time.

Errors and error management

Errors made by the controllers can have consequences either on the ground station or on the satellite and its operations.

In case of the ground station, the worst thing that can happen because of wrong handling is a loss of telemetry from a satellite for a few dozens seconds. If the communication loss is due to a wrong command, the reception path can be reestablished with a new command. There is no single command that can "jam" the computer system as a whole (and a second computer is always ready as "hot-backup"). And even if the computer system should break down entirely, it is always possible - although tedious - to configure and operate the ground station equipment manually, via the local Monitoring and Control computers. The control interface for the ground station therefore checks only that the command are syntactically correct, and whether the parameters are within the allowed limits. After that, the commands are immediately sent for execution.

Error management is somewhat different for satellite operations. Satellites are quite simple systems, where the number of components is kept to a minimum. In develop the necessary competence in course of time. The operational tasks of the controllers in Usingen were modelled after those of the controllers at GSOC. The following considerations regard in first hand the work of the satellite controllers and the way it is supported by the monitoring and control system.

Cognitive requirements of the task

The type of operations and the background of the controllers at the ground station were described in Section 5.3.

The type of work of the controllers does not require the simultaneous (parallel) collection and evaluation of large amounts of data; normal cognitive limits are not exceeded and the workload is not stressful. All communication with the equipment under control takes place via the computer interface, so that no previous "tactile feeling" is lost because of the computer interface.

In satellite control, there is no need for direct manipulation of any device where the human acts in a sensomotoric feedback loop (e.g. with a joystick). No special sensomotoric skills and manual dexterity are therefore required, besides the fact that the controllers must be proficient in the use of computer terminals (they are). There are no formal requirements about typing speed or precision.

The typical work actions do not require continuous attention or fast response times. Normal satellite operations are scheduled hours or even days beforehand and in general do not follow very strict timings. The pace of the work does not represent a cognitive overload.

In case of failures at the ground station, the controllers send commands to configure the ground equipment by connecting spare devices. After that, the ground station technical group is informed of the problem and no further action is required by the operators.

In case of alarms from a satellite, the operators must follow instructions contained in the handbooks. Correctness and precision in the execution of the task is more important than speed. The operators are always two per shift and can support each other in failure analysis. For this reason, even unplanned operations and emergencies do not contribute to work overload. For every alarm it is indicated how to proceed in a step-by-step fashion, what data to check, and what routines antenna is positioned in the search window for closer tracking of the satellite. Telemetry reception can then begin with no other additional procedure.

In some cases - e.g. for testing and maintenance purposes - it might be needed to address the single devices directly; special display masks are available for this task. On these pages, monitoring and control data are presented side by side. The control parameters are filled in clear text, and then sent for execution. After a few seconds, the new monitoring data indicate the new state. As long there is a difference between set-point and monitored data, the set-point values are indicated in reverse colour on the screen. In general, however, the direct control of single devices is not part of normal operations, but is required only for special purposes, e.g. to test the equipment.

The number of macro commands for normal operations is about 40. The total number of macro commands for device and software configuration (where all possible path combinations are considered) is about 350.

5.5 Evaluation

The ground station has been in operation since 1989. In general, the DBP Telekom is satisfied over the system, and the personnel was able to become more responsibilities in course of time.

The design of the ground station, especially in respect to the monitoring and control of the ground equipment is evaluated here with the background of the theory presented in Chapter 2, 3 and 4.

TASK ANALYSIS

General aspects

No task analysis as such about the work of the satellite controllers was made, but the initial operational requirements indicated clearly that a non-specialised staff should be able to conduct operations. In addition, the work routines and activities in satellite control are long established. DBP Telekom cooperated closely with DLR/GSOC - where satellite control operations are carried out routinely - to standby are shown framed. The colours maintain their meaning, a green, filled symbol indicates an active and operative device; a framed symbol in yellow indicates a disconnected device, which in addition generates a warning. Colours and symbol framing/filling are two parallel coding features that make two different types of information easy to perceive and understand.

When the ground station entered in service, satellite telemetry data was displayed in clear text with no hierarchical processing. Therefore more attention was required by the operators than for the control of the ground station. A system upgrade including full graphical representation of satellite data is now operational and running on each workstation. The system, called Graphical System Manager (GSM) is basically a "point-and-click" interface to the ground station monitoring and control system as well as to the satellite data. With GSM-software one can point with the mouse and click at one symbol on the screen and the data related to that subsystem / device one level lower will "pop up" and be displayed.

Ground station control

The operations of the ground station are remotely controlled by the use of ready command sequences. Such commands were defined for the control of devices / subsystems / systems as well as entire satellite paths. These commands are called at the ground station "macro"-commands, because they consist of several binary control packets for the single devices.

For all nominal operations and all alternate configurations there are pre-programmed macros. In case of alarm, the operators only need to react by typing on a keyboard the macro instruction to set the new configuration.

The names of macro control files follow a structured naming scheme. The name may have a maximum of eight characters and is composed of a combination of abbreviations indicating the device/system addressed and the function to perform.

For instance, in **DF1TM4A9** one can recognise three abbreviations. **DF1** indicates the satellite DFS1, **TM4** shows the telemetry chain number 4 and **A9** the antenna 9. With this command, the full reception path for DFS1 telemetry via Antenna 9 and Telemetry Chain 4 is established. All the devices on the reception path (they are about 20 for one satellite) are configured with the appropriate parameters (frequency, bit rate, synchronisation word and others) and the replaced by a free one or by the spare, that is shown on the screen as framed. Currently active chains and groups are shown filled.

Error/failure search starts from the top-level representation. If any symbol on screen turns away from green, a more detailed picture can be selected at a lower hierarchical level to identify the problem source. For instance, the high-frequency group 4 (HFG4) is represented with a symbol in the main picture, but it is possible to select the picture showing in detail the single devices of HFG4 (Figure 5.7).

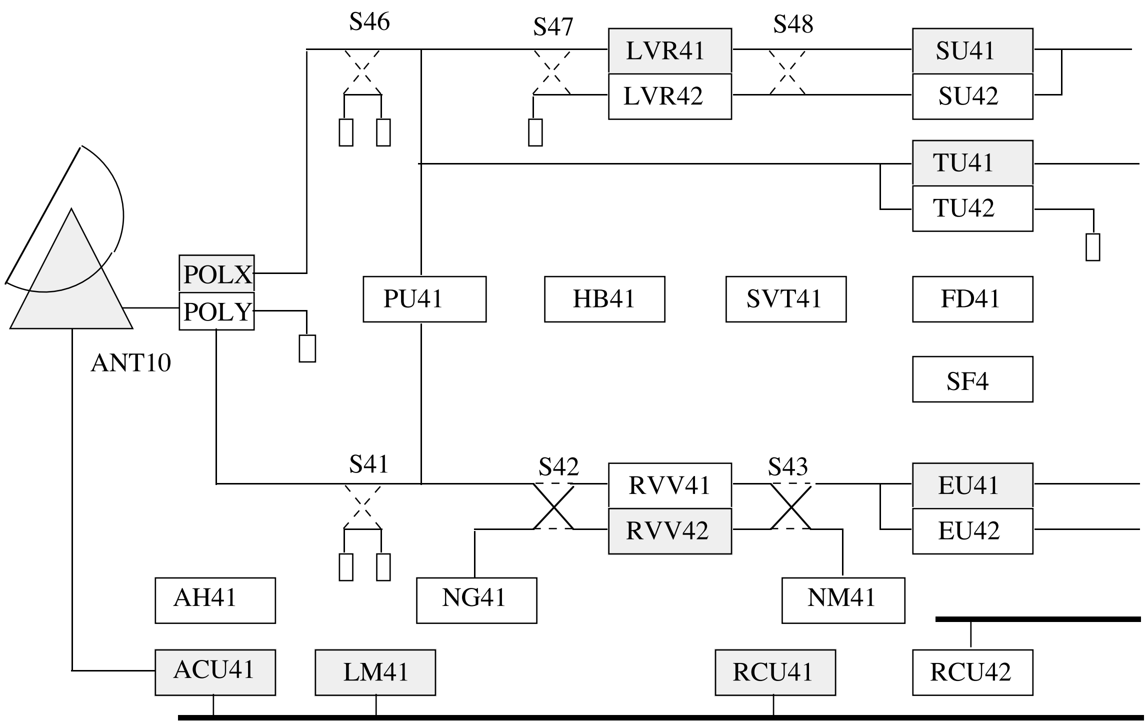

Figure 5.7 Screen representation of the High-Frequency Group 4 (DFS system)

Most devices and subsystems are built with redundancy, e.g. two devices or subsystems are connected in parallel and only one carries out the required function. In the graphical screen presentation, active devices / subsystems (e.g. on a transmission or reception path) are presented filled, while the devices on

The reason for this order is straightforward. In case of a communication alarm, all other information about the device/system is no longer valid. If the device is in LOCAL control mode (e.g. for maintenance), alarm states might be due to test procedures and do not need to alarm the operators. A general alarm is more important than a warning and is therefore shown with higher priority. Only when no conflicting data is present, a device/system is shown in green.

On the graphical screens each device, subsystem and system is represented with a symbol. The colour of the symbol shows whether any alarms are present and, in such case, their relative importance. The connection states of the switch matrix are shown in alphanumeric texts indicating what chains are connected to what antennas. Figure 5.6 shows the general system layout on one of the terminals in the control room.

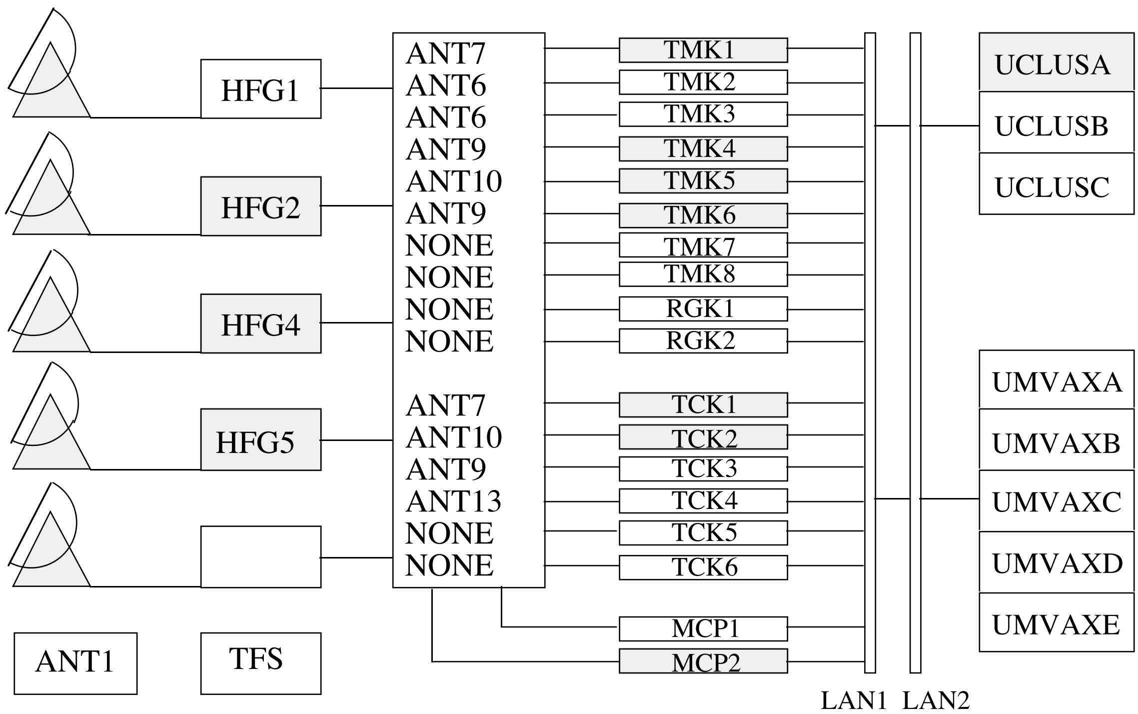

Figure 5.6 Screen representation of all ground station systems

The layout displayed in Figure 5.6 is used to support the replacement of chains and groups. In case of failure, a telemetry, telecommand or ranging chain is

Some monitored data, like e.g. synchronisation and signal level information, are shown at the lowest levels as warnings and at higher levels in some cases as warnings and in other cases not, depending on the current configuration of the device / subsystem.

All ground system functions are documented. The satellite controllers can trace back the source of all alarms with help of logical schemes.

Graphical representation

At the lowest monitoring levels (level 1,2 and 3) the parameters from the devices are shown in clear text (Level-1: raw hex data; Level-2: direct parameters; Level-3: derived parameters). All subsystems and systems are shown graphically at the higher hierarchical levels (level 4, 5 and 6). On graphical screens the devices and the systems are shown with boxes or similar symbols, where the inputs and outputs are clearly recognised. The state of a device or system is shown by the colour of the box. The colours indicate normal and alarm states:

Green: device OK, nominal state, no alarm
Blue: communication-alarm. No monitoring data is available about this device.
Red: general alarm. The device cannot perform its function.
Yellow: general warning. The device is still operating, but the state of some parameters is not nominal.
Orange: operating mode LOCAL/REMOTE. The device is in LOCAL mode, no remote control is possible. Remote monitoring is usually possible.

When several indications are present at the same time in alternative to green as basic coding, only the most important one is shown. The hierarchy follows this principle:

1 Blue (communication alarm)
2 Orange (control mode)
3 Red (general alarm)
4 Yellow (general warning)
5 Green (device OK)

In the hierarchical structure, devices are connected together in subsystems and subsystems are connected in systems. A device failure may lead to a system failure or not depending on the type of malfunction, whether a redundant device can be used as replacement, etc.

In general, alarms and warnings at a level are connected in OR-fashion to alarms and warnings respectively, one level higher. A device in LOCAL-mode will make the respective subsystem also appear to be in LOCAL-mode; the same holds for the whole satellite path. Similarly, a device WARNING is reported as SUMMARY WARNING at higher levels.

Slightly different is the handling of device STATUS ALARMs. A device ALARM is considered to be a subsystem or system ALARM if the alarmed device is ONLINE and connected on a satellite transmission / reception path. If the device is OFFLINE, the alarm from the device is reported only as WARNING at higher levels. This evaluation of alarms is oriented to the operational needs. A malfunctioning device does not need to drive entire display pages red if the operators are aware of that information and the device is disconnected.

The SETUP parameters are connected via AND-functions and the reason is immediate: all devices must be configured for a satellite for the path as a whole also to be configured. Obviously, it does not make sense to set the receiver to DFS1 frequency and load the PCM-preprocessor with the synch word for DFS2. In such case SETUP=NONE.

These principles for monitoring are easily understood by the ground station personnel and make the monitoring of the system particularly easy. The operators work normally only with the display pages at the highest levels. Any new failure is immediately reported through all levels by the monitoring and control system. If the operators notice a change of colour on the screen symbol for a system, they can immediately trace the source by displaying the appropriate pages for subsystems and devices. On each page the exact alarm / warning source(s) at lower levels are displayed in a different colour, so that the search is immediate and does not have to proceed blindly. In addition, all failure and state changes are logged with the related time-stamp in a separate file and displayed on a dedicated monitor.

COM STAT (*communication status*) shows whether the information link from the device/subsystem/system operates correctly. An alarm state shows that no more monitoring packets are coming from the device. In case of **COM STAT=ALARM** all other information from the device that is stored in the station computer is considered to be outdated and therefore no longer relevant.

CTRL MODE (*control mode*) shows whether a device is switched over to local mode. In such case, the device can no longer be remotely controlled, though it continues to send monitoring packets as long as it is not disconnected from power mains. A device is switched to **LOCAL**-mode only for maintenance, so that eventual alarms do not need to be considered.

The device **STATUS** (*general alarm*) is a high-priority alarm indication about the device. It might be generated from the device itself or derived from the information packets of other devices. When **STATUS=ALARM**, the device is no longer operative.

The **SUM WARN** (*summary warning*) shows a non-normal operating state, which is not necessarily an alarm. The summary warning is the OR-connection of all warnings and non-nominal states reported by a device. Similarly to the general STATUS, also the summary warning can originate from the device itself or be derived from other data.

The **SETUP** is a shorthand form to show whether all satellite-dependent parameters in a device, chain or system are consequently programmed for the same satellite.

The **OP STATE** (*operational state*) shows whether a device is **CONNECTED** (on a direct satellite telemetry or telecommand path) or in **STANDBY** mode.

In the reduced, general representation there are also some device-dependent parameters that show some special state (e.g. the carrier **LOCK**-state in the receiver).

This representation provides for consistency. All the data from each device (some devices deliver a couple of dozens parameters) are logically connected into the main parameters, so that - at least from an operational point of view - all devices present a similar monitoring interface.

The analysis and search for failures in the ground station becomes much easier thanks to this hierarchical representation. When a problem arises, it is shown up to the highest representation level and the failure search is conducted by "zooming in" the faulty equipment.

The general representation for monitoring

In addition to the hierarchical structure, what was necessary to facilitate the operations of the station was a *general representation* for the monitoring and control of each device, subsystem and system. In other words, data from each device / subsystem / system would be presented in a consistent and similar way. Otherwise the operators would have had to monitor several hundred parameters and mentally relate these data - this task alone would have taken most of their energies. An additional source of complexity was that devices from different manufacturers are monitored in different ways; also the names of equivalent parameters differ from each other.

The solution I proposed (and that is currently implemented) looks as follows. For every device / subsystem / system the monitoring and control system answers the following questions:

- Is communication to/from the device possible?
- Is the device/system operative?
- Is the device/system remotely controllable?
- What is the device/system currently doing?
- What can the device/system do?
- How well if the device/system performing its function?

The monitoring data for a device is evaluated and formulated in a few basic parameters:

Parameter name	State
COM STAT	OK/ALARM
CTRL MODE	REMOTE/LOCAL
STATUS	OK/ALARM
SUM WARN	OK/WARNING
SETUP	DFS1/DFS2/DFS3/TVSAT
OP STATE	IDLE/ACTIVE

the devices are manufactured by different companies, the data formats differ widely (ASCII text, binary-coded packets, etc.). The control units, the Front-End Processors and the Monitoring and Control Processors convert these data in standard packets with uniform structure (*International Format for Space Data Systems*) and put a time stamp on the data.

The monitored data can be displayed directly at the workstations, but it makes little sense if it is not considered in the context of data from other devices. For example, a loss of synchronisation in a PSK-demodulator might indicate a serious problem if the device is inserted in the reception path, the antenna is pointed to the satellite and all other devices work properly. If the antenna points somewhere else or the satellite reception path is otherwise disconnected, then the loss of synchronisation is not a problem but a normal and expected operational state.

This means that many of the monitoring parameters cannot be checked for alarm states or limits alone but must instead be compared with other parameters and therefore be considered in a wider context. For example, the loss of synchronisation will be checked with the antenna angles, the level of the received signal and the operational states of the other devices along the signal path.

In order to simplify the monitoring and control operations, the ground system was hierarchically structured in six levels[3]. This structure follows similar guidelines to those indicated in Section 3.3. The levels were defined as follows:

1 original hexadecimal data
2 original data from the devices in clear text (parameter names and states)
3 derived data from the devices, according to the scheme described below
4 derived data for subsystems
5 derived data for systems / complete satellite paths
6 station overview: all systems, satellites and station computer

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[3] A pertinent question at this point is, why just six and not a different number. The number of representation levels had been discussed before I began my assignment and was finally decided in a meeting that took place shortly after I began my activity at DLR. The number of levels *had* to be six; the funny thing is, I was left alone to decide what those levels would be and what kind of data they would encompass.

5.4 The User Interface

Operational software packages

The different software packages installed in the station computer provide for:

- telemetry processing TV-SAT
- telemetry processing DFS1
- telemetry processing DFS2
- telemetry processing DFS3
- telecommand TV-SAT/DFS1/DFS2/DFS3
- ranging TV-SAT/DFS1/DFS2/DFS3
- orbit determination from ranging data
- archiving of telemetry and ground system data
- operations scheduler for the generation of (semi-)automated satellite and ground system control sequences
- data exchange with GSOC in Oberpfaffenhofen.

Not all these routines run at the same time. Only the telemetry processing for the four satellites and the data archiving process must always be in operation, other routines are activated on a "when needed"-basis.

The Operations Scheduler (OPS) allows the satellite or ground station subsystem engineer to write, test, and submit procedures aimed to monitoring telemetry parameters, setting value thresholds for parameters, and even define procedures to be activated automatically in case the preset thresholds are exceeded. Procedures that are started automatically can always be overridden by the operators, if so needed.

Ground station monitoring - the hierarchical structuring

All monitoring packets from the ground station devices are collected and processed in the station computer (STC in Figure 5.5). Almost every device in the ground station delivers a status packet with current information about its state. The delivered information is for example the indication of the selected frequency in transmitters and receivers, of the connected paths in the switch matrix, the values of the pointing angles for the antennas, etc. Due to the fact that

There was an explicit choice that the satellite control group does not work in direct contact with the ground station devices, but only configure them remotely from the control room. The attention of the controllers has primarily to be devoted to the satellite systems, so the ground station was designed to be operated easily, and without requiring that the controllers dedicate too much attention to learn about its functions. As a result, their knowledge of the ground station is mainly operative. In case of ground equipment failure, they connect spare systems via remote control.

If the emergency procedure does not bring the desired result, the controllers must contact system engineers for the ground station or for the satellite and who are "on call" 24 hours per day.

There are important differences between the work of controllers at the satellite ground control station and operators in processing and production plants; these differences depend in part on the nature of the task, in part of the tradition in this field. There is no process to optimise on the basis of continuous parameters. Instead, operations are carried out according to schedules prepared in advance. In general, satellite controllers are busy all the time, but few work tasks require fully dedicated attention; this allows for flexibility in the organization of the work.

The satellite controllers have a general - but not in-depth - knowledge of the satellite, its subsystems and of the ground station. Obviously, in course of time the controllers learn about satellite and ground station operations and become therefore more independent in their work. DBP Telekom has made a realistic choice in deciding that in order to use own personnel for satellite control, they had do build up experience in close contact with the industry and GSOC for a period of several years.

and for a preliminary evaluation and execution of corrective actions in case of failures. The ground station technical personnel is responsible for maintenance and repair work on the ground station equipment. The satellite subsystem engineers are responsible for the different subsystems on the spacecraft (orbit, power, payload, thermal, etc.). The satellite controllers and the technical personnel are on shift duty, each group with two people per shift, so that constant presence is ensured. The subsystem engineers work normal hours, but must be reachable all the time.

The controllers at the ground station are young people (in general between 20 and 30 years of age) recruited among the technical personnel of DBP Telekom. Their average education is at the level of technical high school, with specialisation in electronics / communication. The motivation for this work is high both because the task is challenging and qualifying and also because Usingen is an attractive location. In general, the atmosphere at the ground station is pleasant and relaxed. In total, about fifty people work at the spacecraft control centre in Usingen, including shift personnel, engineers, technicians and managers. Almost all the staff is male.

Work operations

Satellite operations are carried out following a *daily plan*. This plan is decided a few days in advance for each spacecraft by the subsystem engineers, under the coordination of a supervisor. The main task of the controllers is to see that the commands are radiated at the scheduled time and verify via the telemetry that their execution on the spacecraft was successful.

In case of anomalies, the controllers have to follow procedures that have been defined and planned in advance and that are described in a step-by-step fashion. These procedures are listed in handbooks and are contained in files that can be recalled and prepared for execution. Emergency procedures follow basically a similar pattern:

1. Identification of the problem source
2. Definition of a new configuration with switchover to spare unit(s)
3. Monitoring of related parameters and of their thresholds, as verification that the problem was solved.

5.3 Control Operations

Operational concept

According to the operational concept of the DBP Telekom, the ground system is monitored and controlled concurrently with the satellites from the main control room. The Control Centre has the responsibility for the following spacecraft operations (some of the manoeuvres are planned together with GSOC in Oberpfaffenhofen):

- monitoring of spacecraft orbit and attitude, with tracking (ranging) performed every three hours for each spacecraft
- execution of station-keeping manoeuvres planned by GSOC
- payload housekeeping, depending on users' requests and transponder load
- seasonal operations, e.g. earth sensor switchover during earth shadow periods (spring and autumn), payload switch ON/OFF during the same period (TV-SAT only), or battery reconditioning.

In addition, following operations shall be taken over by Autumn, 1993:

- orbit determination and prediction
- planning and execution of station-keeping manoeuvres (East-West every week; North-South every two weeks), and manoeuvre calibration

By the end of 1993, all activities related to the satellite flight dynamics (orbit determination and correction) shall be carried out autonomously by the Usingen control centre, with backup by specialised personnel at the Telekom Technology centre (FTZ) in Darmstadt (100 km from Usingen). The two sites will be linked via redundant 64 kbit/s data lines. In this way, the Usingen station, FTZ, and GSOC shall be internetworked and may act as a single operational unit during the operational lifetime of the satellites.

Ground station personnel

The staff at the ground station is divided in three groups: satellite controllers, ground station technical personnel, and satellite subsystem engineers. The controllers are responsible for the execution of the scheduled satellite operations

Data collection for the telemetry, telecommand and ranging baseband devices located in the operations room is carried out by the Front-End Processors, with one dedicated IEEE-488 bus for each baseband chain. The Front-End Processors send the collected data to the central Monitoring and Control Processors in form of data packets.

Communication between the Front-End Processors, the Monitoring and Control Processors, the Station Computer and the Workstations takes place over a Local Area Network (LAN) of Ethernet type. This network consists of two physical channels in order to increase its reliability. Data routing on the network is controlled by the operating system and is transparent to the application software.

The two Monitoring and Control Processors form a redundant concentration point for all data; they collect about 1500 local state values directly or via the Front-End Processors (PDP 11/73), process them for display on local terminals and send them further to the station computer as data packets. The basic update cycle is 2 seconds; in order to reduce the data load on the station computer, only packets whose content has changed during the last cycle are passed along. All data packets are marked with a time stamp to identify their chronological sequence. These data packets follow a standard format used by space agencies. In this way the station computer can run the same basic type of software for processing of satellite telemetry as well as ground station monitoring and control data.

The ground station devices are remotely controlled via packets with a structure similar to that of the monitoring packets. The only difference is that the data flows in the opposite direction, from the station computer to the devices.

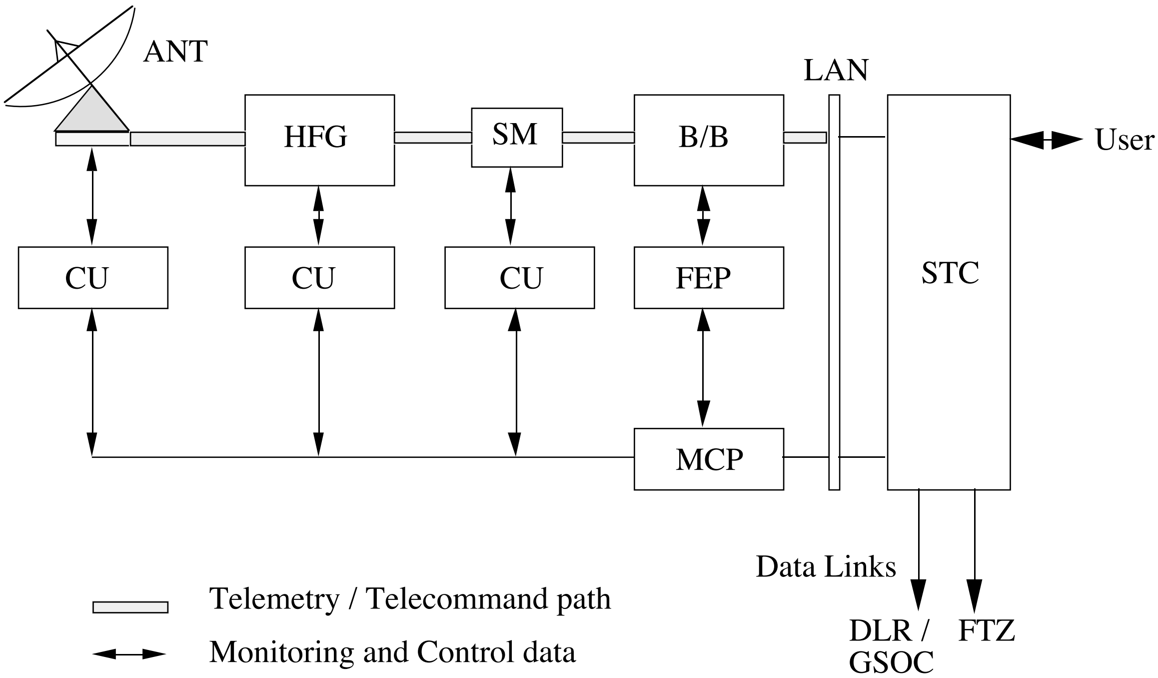

Figure 5.5 Monitoring and Control concept for the ground equipment

HFG: High-Frequency Groups; SM: Switch Matrix; B/B: Baseband equipment
CU Remote Control Units, 12 x 80186 Processors
FEP Front End Processors, 12 x µPDP 11/73
MCP Monitoring and Control Processors, 2 x PDP 11/83
LAN Ethernet-type Local Area Network, 2x redundant
STC Station Computer, 3 x VAX 8260
DLR/GSOC German Space Operational Centre in Oberpfaffenhofen (450 km)
FTZ Research and Technology Centre of the DBP Telekom, in Darmstadt (100 km)
Data links: 9.6 kbit/s, upgrade to 64 kbit/s.

The states of the antennas, of the high-frequency equipment in the GHz range and of the switch matrix configuration are collected by the 80186-based control units and sent to the two central PDP 11/83 Monitoring and Control Processors via redundant IEEE-488 buses. The connection between antenna buildings and the central building is realized with parallel-serial converters and optic cables.

Figure 5.4 Main control room in the satellite ground control station (source: Dornier System; from Altmann and Piani, 1989)

A terrestrial communication link at 9.6 kbit/s is installed between the Usingen control centre and the GSOC complex in Oberpfaffenhofen; the distance between the two sites is about 450 km. A 64 kbit/s link shall be operational in the near future.

The basic monitoring and control structure is shown in Figure 5.5. The monitoring and control system is hierarchically structured; it is composed of two Monitoring and Control Processors (MCP) of type PDP 11/83, twelve Front-End Processors (FEP) (μPDP 11/73) and twelve 80186-based remote Control Units (CU). The FEPs are the same control computers used in the telemetry, telecommand and ranging chains.

The ground operations system has been designed for easy expansion, allowing for integration of six additional telemetry and six telecommand chains in the existing monitoring and control structure.

The connection of the different baseband chains with the high-frequency groups takes place over a switch matrix with about 60 switches. The switch matrix is built in such a way that repair work on any one switch does not affect any unrelated transmission or reception paths.

All high-frequency and baseband devices are mounted in 19"-racks and are connected to FEPs via standard IEEE-488 bus interfaces. The devices can be operated locally via their front panels, but normally all monitoring and configuration operations take place remotely from the control room.

Monitoring and control of the ground equipment

A central station computer processes all monitoring and control data from the ground station equipment and all telemetry and telecommand data from the satellites. The station computer is composed of three VAX 8260 computers in cluster configuration installed in a cooled room. Two VAX units in master/backup configuration process the incoming data in real time; the third unit is mainly used for offline analysis but can also be used as cold redundant unit. The switchover between the computers is realized with the use of common disk stores.

The satellite and ground system control operations take place from the main control room (Figure 5.4). There are a total of six workstations. Four are used for the control of one satellite each and one workstation for the monitoring and control of the ground station equipment. A sixth workstation is installed in a room close to the main control room and is normally used for offline telemetry data analysis, for training, and for software maintenance. It can also be used as additional operational unit, if needed.

Figure 5.3 Baseband equipment room (source: Dornier System; from Altmann and Piani, 1989)

Similarly there are five telecommand (TC) chains, three for DFS1, DFS2 and DFS3, one for TV-SAT, and one spare. Each TC-chain is composed of a TC-Encoder, a Phase Modulator, a 70 MHz Modem and a Front End Processor (FEP). The Front End Processor interfaces to the LAN and monitors/controls the TC-chain devices.

Two ranging systems (RG-chains) are in use at the ground station; they are fully equivalent and can be used interchangeably with any of the satellites. The ranging systems are interfaced to the LAN via FEPs, in the same fashion as for the telemetry and telecommand chains.

Figure 5.2 Antennas for Telemetry and telecommand for the DFS satellites (source: Dornier System; from Altmann and Piani, 1989)

The satellite telemetry data is processed via five telemetry (TM) chains, one allocated to each of TV-SAT, DFS1, DFS2, DFS3 and one spare. Every TM-chain is composed of a 70 MHz Receiver, a PSK-Demodulator, a Bit Synchroniser, a PCM-Preprocessor and a Front End Processor (FEP). The Front End Processor has the double function to convey the telemetry packets from the PCM-Preprocessor on the Local Area Network (LAN) to the station computer as well as to monitor and control the devices in the Telemetry chain. The use of FEPs as LAN-Communication units helps realise a standard interface with all baseband devices and simplify the monitoring and control operations of the station computer.

The Ground Operations System (GOS) design is structured in a modular fashion; its layout was designed in compliance with the above listed requirements. For the support of each satellite are necessary one dedicated antenna, one telemetry and one telecommand path. Telemetry reception from all satellites must take place continuously and without interruption, so and dedicated path is necessary for each satellite. Telecommands are sent on a when-needed basis, usually a few times per day for each satellite and mostly according to a predefined schedule. Ranging is performed every three hours for each spacecraft. The same ranging equipment can be used for either satellite and is connected in alternative to the telecommand equipment.

An antenna with dish diameter 18.3 m is used for the uplink and the downlink of the payload signal to/from the operational DFS satellite. Because of its size, this antenna can track the satellite with high precision (up to 1/1000 degree) in monopulse mode and thus can deliver reference pointing angles to a smaller antenna (4.5 m) that is used for telemetry and telecommand. A 9.5 m antenna is used to track the satellite at the orbital position 33.5°E, because in this case there is no larger communication antenna to deliver pointing angles accurate enough to be used for tracking and orbit determination. The third DFS satellite is tracked via a 11.5 m antenna. Two of the telemetry/telecommand antennas for the DFS system (ANT9 and ANT10) are shown in Figure 5.2 (notice that the antennas are numbered following organisational criteria at the ground station and independently of this specific project).

In two buildings close to the antennas for DFS and TV-SAT are installed four High Frequency Groups (HFG) with the devices: Upconverters, High Power Amplifiers, Low Noise Amplifiers, Downconverters and Testconverters for ranging calibration. In the HFG groups to support the DFS satellites all devices are doubly redundant with two similar units connected in parallel. In this way is provided for fast online replacement in case of failure. The HFGs in the two antenna buildings are connected to the central baseband equipment room via underground coax cables at 70 MHz intermediate frequency.

In the baseband equipment room (Figure 5.3) are installed all baseband (B/B) devices for telemetry, telecommand and ranging, as well as the auxiliary equipment for frequency generation and distribution and for remote monitoring and control.

- computer-based system for remote monitoring and control of the ground station equipment
- high reliability and availability of the ground station equipment (redundant system design with no single-point failure, 99.95% availability factor)
- ease of operations; routine operations for both ground station and satellite control must be conducted with only two people per shift.

Ground station design

The ground station consists of about 100 complex devices. A computer-based monitoring and control system is needed to control them remotely with reduced workforce. A system overview is shown in Figure 5.1.

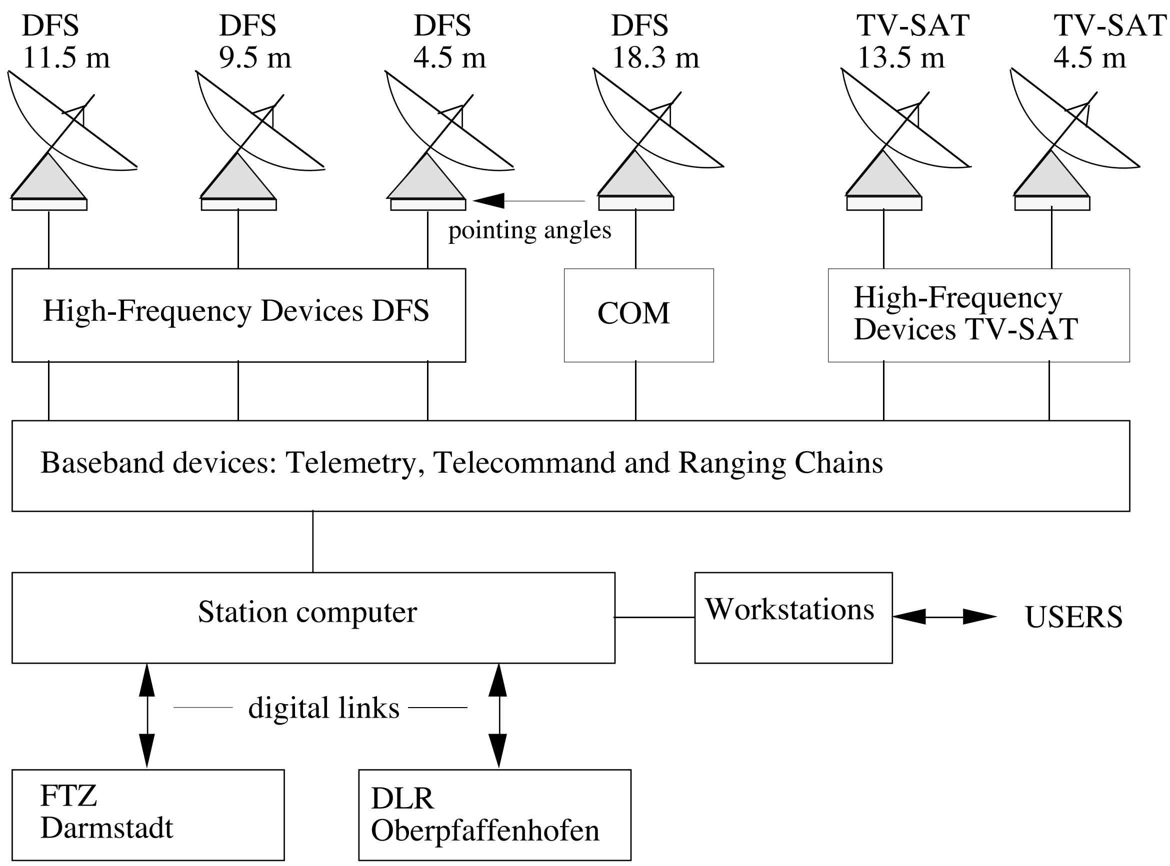

Figure 5.1 Satellite ground control station in Usingen (Germany); system overview

hofen (near Munich) developed the operational software for telemetry, telecommand and ranging, for data archiving, and for ground station operations.

The control centre at Usingen was taken in operation in June 1989, two weeks after the launch of DFS1. The routine operations for DFS and TV-SAT were gradually transferred from Oberpfaffenhofen to Usingen in the period from Autumn 1989 to Spring 1990.

5.2 The Ground Station Design and Operations

Ground station requirements

The DBP Telekom defined the following requirements for the Telemetry and Telecommand (**TTC**)[1] operations at the Usingen ground station:

- simultaneous and continuous operation for four satellites, with expansion possibility to support two further spacecraft
- Ku-Band telemetry at 11 GHz; the telemetry signals from both satellites are pulse-code modulated at 512 bit/s data rate.
- Ku-Band telecommand (DFS at 14 GHz, TV-SAT 17 GHz); telecommand signals are pulse-code modulated at the rate of 500 bit/s.
- continuous radiation of a beacon signal for TV-SAT antenna pointing control
- Ranging[2] for one satellite at the time without interruption of telemetry reception

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[1] To avoid confusion between satellite operation and ground station operation, Telemetry and Telecommand (TTC) refer to the satellite, while Monitoring and Control are related to the ground station equipment.

[2] Ranging is an operation to determine the exact linear distance of the satellite from the antenna. Ranging is basically performed by sending pulse signals to the satellite and measuring the delay in their retransmission to earth. Knowing the geographical location and the pointing angles (azimuth and elevation) of the antenna, with the measured distance from the satellite it is possible to compute the exact spatial position of the spacecraft.

was not planned to be used for direct broadcasting, dishes of about 80 cm diameter allow good home reception.

d. Provision of TV reportage mobile services from and to TV studios (transponder 30/20 GHz).

The satellites DFS1, DFS2 and DFS3 were launched in June 1989, in July 1990, and in October 1992 respectively.

TV-SAT system

TV-SAT is a different kind of satellite, used for direct broadcasting of TV programs; this satellite was initially conceived in the 1970s. At the time, earth antennas had to be very large (in the order of some meters in aperture diameter) to offset the effect of high noise figures of the electronic components then available. In order to allow home reception with small antennas, the satellite had to transmit with high power; this meant a reduction on the number of channels, because the on-board power source is also limited. The satellite EIRP (Equivalent Isotropic Radiated Power) is 65 dBW and the transponders radiate about 200 W each at 27 MHz bandwidth; the power per channel is thus 10-20 times higher than for conventional communication satellites.

TV-SAT broadcasts five TV channels in the new European D2-MAC standard; each TV channel can alternatively carry 16 digitally coded stereo radio channels. Main receiving area is Germany, where an antenna dish of about 50 cm diameter is sufficient to receive TV signals with good quality. The satellite TV-SAT was launched in August 1989.

Both satellites DFS and TV-SAT are built by a German company consortium led by Siemens and MBB.

Ground station

The company Dornier developed and delivered a complete hardware system for the processing of the high-frequency signals for the control of the satellites. The system includes antennas, radio equipment, and auxiliary units. The German Space Operations Centre (GSOC) of the German Aerospace Research Institute (*Deutsche Forschungsanstalt für Luft- und Raumfahrt*, DLR) in Oberpfaffencontrolled from other sites). This facility is the first of its kind in the Federal Republic of Germany.

The decision to develop a satellite communication system was taken by the *DBP Telekom* (then called PTT Administration *Deutsche Bundespost*) at the beginning of the 1980s. The system consists in two satellite families: DFS and TV-SAT.

DFS system

The DFS (*Deutscher Fernmelde-Satellit*, *German Communication Satellite*) is used for the transfer of data and voice as well as for the distribution of TV channels; it is named after the astronomer Nikolaus Kopernikus (1473 - 1543). DFS was used to establish the first direct communication links between East and West Germany after the political changes of 1989-1990 (at the time when the Berlin Wall fell, there were only about 120 phone channels between the two countries and no wideband carrier).

The satellite system DFS Kopernikus comprises a total of three spacecraft models in geostationary orbit. The satellite DFS1 is located at 33.5°E, DFS2 has the orbital position 28.5°E and DFS3 is positioned at 23.5°E.

The main functions of each of the DFS satellites are the following:

a. Provision of up to 2000 telephone links inside Germany via two transponders in range 14/11 GHz and one transponder in range 30/20 GHz.

b. Data exchange inside Germany, notably:

- full duplex digital links at 64, 128, 256, 512, 768, 1536 and 1920 kbit/s;
- simplex digital links for point-to-point and point-to-multipoint (up to 16 parties) connection.

The data exchange services are provided by two transponders in the range 14/12 GHz, both with data transfer rate 60 Mbit/s. The data services are integrated in the ISDN network of the DBP.

c. Broadcasting of up to five TV and audio stereo channels via the 14/12 GHz transponders for reception by small and middle size earth stations (dishes in diameter range 3.5 - 4.5 m) and feed into local cable networks. Although DFS

5 Case Study: The Monitoring and Control System of a Satellite Ground Control Station

The following case study is the description of a project in which I have participated between 1986 and 1989. My responsibility was the design of the user interface of the control centre for the satellites of the German communications administration Telekom (DBP Telekom). This project has been reported in two papers, Altmann and Piani (1989) and Altmann, Damiano, and Piani (1991).

The chapter is structured as follows. In Section 5.1 the satellite system is introduced; the structure of the ground control station and its monitoring and control system is described in Section 5.2. Section 5.3 describes the work operations of the ground team and Section 5.4 deals with the user interface in relation to the task operations. The chapter terminates in Section 5.5 with a critical evaluation *a posteriori* of the monitoring and control concept and of its implementation.

5.1 General Features of the DFS/TV-SAT Satellite Systems and of the Ground Control Station in Usingen

The satellite ground control station of the DBP Telekom is located in a small town, Usingen, about 50 km northwest of Frankfurt/Main. From this ground station three communication and one TV broadcast satellites are controlled. This station has also communication facilities for the satellites of the European Broadcasting Union (used for the exchange of TV news and other programs among all European public TV administrations), as well as for the Intelsat satellites over the Atlantic and the Indian oceans, with direct phone links between Germany and the Americas, Africa, Asia and Oceania.

The user interface described in this chapter is used for the monitoring and control of the ground equipment for telemetry and telecommand of the four satellites of the DBP Telekom (the Intelsat satellites for intercontinental communication are