INTERACTIVE DISPLAY AND CONTROL FOR SATELLITE SUPPORT GROUND STATIONS

Owen C. Holzborn
Senior Software Engineering Specialist
Ford Aerospace & Communications Corporation
Sunnyvale, California

ABSTRACT

This paper describes operator interface design and implementation of control and monitor display subsystems for satellite tracking, telemetry and commanding stations. It presents an overview of station configuration, functions and operating modes. These are used as the basis for a discussion of the human/machine interface characteristics required for effective operation and maintenance of the station. This includes display techniques, operator control mechanisms, methods for minimizing operator input requirements (and, hence, sources of human error), and system adaptation to operator skill level. Finally, table-driven display generation and control processing approaches and their inherent flexibility and compactness are presented.

INTRODUCTION

The typical satellite support ground system network includes a central master control station and several geographically dispersed Tracking, Telemetry and Commanding (TT&C) stations. The TT&C station provides an interface between the ground based system and the satellite for commanding and uploading (uplink), satellite tracking (for refinement of orbital parameters), and vehicle health, status and payload telemetry retrieval (downlink). The master control station and its TT&C stations communicate via wideband satellite communications links, narrowband landlines, or both.

Figure 1 shows a typical configuration using wideband communications as the primary link with a narrowband backup. The master control station performs planning, orbit determination, command generation, network scheduling, and operational control and vehicle status monitoring during vehicle support operations. It forwards tracking station control and vehicle commanding data to the TT&C station. The TT&C station uses acquisition data provided by the master control station to direct its antenna for satellite acquisition. Once in contact with the satellite, the TT&C station relays commands to the satellite, collects and sends tracking data to the master station for use in refining orbital parameters, and relays satellite telemetry data to the master station. The TT&C station may also record data for later transmission to the master station. Other deployment configurations, including colocated master and TT&C stations are used. These deployment variations may change the interconnection techniques between the master station and its TT&C support equipment, and may combine the TT&C operator interface with master station command and control functions; but do not materially alter the basic requirements for the human interface with the control and status monitoring functions of TT&C station.

The focus of this paper is upon a remote TT&C station, specifically, the computer-aided operational control and monitor (C&M), maintenance and test facilities and the operator interaction techniques used. The design of these facilities is undergoing a major transition in the direction of increased automation. Human involvement is being reduced, for normal operations at least, to duties which can not yet be performed by machines (recording tape mounting and dismounting, fault isolation and equipment maintenance, for example). In the very near future, the major human role will be primarily that of maintenance.

As the level of automated control increases, the interactions with the remaining human operators become ever more critical to effective operation and maintenance activities. Since routine operations are performed without human intervention, only exceptional conditions, those demanding quick and accurate responses under potentially stressful conditions are left to the operator. This then, is the primary challenge facing designers and implementors of the human/machine interface (HMI) in systems for control, status monitoring and automated testing.

The remainder of this paper discusses the functional requirements, HMI design concepts, and software design and implementation techniques which support these requirements and concepts.

TT&C GROUND STATION MAJOR COMPONENTS AND FUNCTIONS

The major elements of a typical TT&C ground station are shown in Figure 2. Major subsystems comprising a TT&C station are the C&M subsystem, the TT&C subsystem, the satellite transmit/receive antenna subsystem (some systems include the antenna as an element of the TT&C subsystem) and the communications subsystem.

The C&M subsystem issues station equipment configuration and antenna pointing commands and forwards vehicle commanding data received from the master station. It monitors station status, command echos, collects and time-tags tracking data (antenna position, range and range rate) and sends this information to the master station. The C&M subsystem extracts telemetry data (including command verification, vehicle health and status, and payload data) from the received downlink signal and transmits it to the master station. The C&M subsystem also monitors equipment status and reports it locally and to the master station.

The C&M subsystem hardware includes a computer/peripheral network to provide the basis for automated control and monitoring. The C&M software executes within this network and provides the interface with the local operator through the C&M console. The C&M console (usually a CRT terminal) is used to report status and alarms to the local operator. It also provides a means for the operator to intervene for manual override, fault isolation testing and repair verification testing. Other major C&M elements provide station timing (using a highly accurate time standard, synchronized with the timing system used by the master station), data and test signal switching equipment, and test equipment.

The TT&C subsystem is divided into uplink and downlink elements. The uplink elements generate the uplink carrier signal, and combine command data and a ranging code with the carrier. The resulting modulated signal is amplified and transmitted to the satellite via the antenna. The downlink elements receive and detect the signal from the satellite, separate any subcarriers used, perform signal processing for all downlink telemetry streams, and process received ranging codes to determine range and range rate. The downlink equipment also includes record and playback elements.

The local communications subsystem connects the TT&C station with its master station facility. It may include an additional satellite antenna for use of wideband satellite links. Narrowband landlines may be employed for low data rate satellites or for backup of the wideband link.

Satellite Support Scenario – A satellite support scenario consists of prepass, pass and post-pass operations. Pre-pass consists of readiness testing to assure the capability of the station to support the operation. The pass phase begins with signal acquisition, proceeds to command the vehicle and readout payload data, and ends upon a terminating command sequence, when the signal is lost as the vehicle drops below the horizon (called fade), or by prearranged schedule. Post-pass operations, when required, usually involve tape playback (and may be delayed to accommodate the need for real time support of another vehicle). These phases require rapid configuration of the station equipment and verification of the data paths through all station equipment and between the TT&C station and its controlling master stations.

Station Operating Modes –Two basic operating modes, with varying degrees of operator involvement, may be implemented. In automatic mode the configuration commands and antenna pointing angles are received from the control station and issued in real time. The second mode, which might be called semi-automatic, allows the local operator to call up prestored, vehicle specific station configurations from a local mass storage device. Once configured (automatically or semi-automatically), the station receives vehicle command data from the control station and relays it to the satellite. Responses from the satellite are relayed back to the master station. Configuration changes during pass can occur in either of these modes in response to change commands. In automatic mode these are received from the master station. In semi-automatic mode the control and monitor display console allows the local operator to make individual equipment changes as directed by the master station site via voice coordination link. Note that prestored operational or test configurations can also be used in automatic mode. The semi-automatic mode, using prestored test configurations, is the mode used for testing under the control of the local operator.

Critical Maintenance Functions – The operational C&M software includes the fault detection functions as an integral part of status monitoring. Detected faults trigger alarm generation at the C&M console to alert the local operator and present initial diagnostic information. These alarms are also reported to the master station. Once a fault is detected, fault isolation is accomplished by the local operator using automated test functions which rapidly localize the fault to the line replaceable unit (LRU). These automated tests allow the operator to perform collapsing loop tests and individual equipment diagnostics from the C&M console. The selection of test signal insertion points, loop-back points, and signal monitoring points is accomplished under the control of the C&M software as directed by the test scenario or operator selections. The equipment level selected to define the LRUs is high (PC board or even chassis) in order to expedite the isolation process and subsequent replacement. This has the benefits of simplified test software, operator procedures, and spares inventories; although individual spare LRUs may be more expensive than in systems having lower level LRUs (component, chip, etc.). The primary motivation for the high level LRU approach is high station availability which requires not only high reliability, but minimum time to restore operations after a fault is isolated.

C&M OPERATOR CONTROL AND MONITOR DISPLAY DESIGN

As can be seen from the foregoing, the effectiveness of the station is strongly dependent upon the ease of operation provided by the human/machine interface (HMI). In the automatic mode of operation little if any need exists for a local operator interface, at least as long as there are no anomalous conditions. But when the semi-automatic mode and fault isolation testing are considered, the human/machine interface suddenly becomes a critical system concern.

What, then, are the important features required of the HMI if we focus on the local operator duties? First, the operator must have effective and flexible input mechanisms for entering control information. Second, the system must provide effective displays of station status and alarm conditions. Finally, the interaction of the operator with the displays and input devices must be designed and implemented with operator effectiveness as the primary goal. These three factors, input devices, displays, and interactive techniques are discussed individually below. Valuable basic design guidelines are provided by Martin (5).

Operator Input Devices –The primary operator input device is an alphanumeric keyboard augmented by fixed or variable function keys. Many system control functions can be activated by function keys, but the additional capability of the keyboard allows input of commentary for logging purposes and non-discrete information such as file names and numeric data. Fixed function keys are those whose meaning do not change with the operating state. However, they may not be enabled in all states. Under software control, variable function keys take on meanings which are unique to a particular operational state. Variable function keys provide the operator access to the currently relevant subset of control actions, any one of which can be triggered by a single key depression.

Display Formats and Techniques –The operator relies upon information presented on the console CRT to determine the status of the system. Decisions as to the next action required are based upon this information. The fundamental requirements for displays are:

> **Clarity** –
> The uncluttered presentation of all needed (and only needed) information gives the operator a clear representation of the current system or task status.
>
> **Organization** –
> Presentation of status and configuration data in a way which reflects system functional data flow and operator task organization minimizes training and operational confusion.
>
> **Focus** –
> By focus, the ability of the display to direct the operators attention is intended. It is necessary to direct attention to fields within the display which reflect exceptions or anomalous conditions.

Clarity is the product of a thorough human factors effort during the system design phase. This effort requires contributions from hardware and software engineers and the operational analysts who will ultimately prepare training material and operational procedures. This joint effort establishes the display hierarchy and the minimal data display and input requirements for each display. Since the system definition evolves during the development cycle, these display definitions must also evolve. This aspect will be important to the discussion of software implementation below. For this purpose, the procurement or creation of a display prototyping tool (2, 3) early in the development process can greatly enhance the end product. Such a tool allows a representative set of users to test the design team's assumptions by exercising the proposed dialogue and provides a means for evaluating simulated versions of the proposed displays.

Organization of the information presented in each display must model the operator understanding of the functional organization of the system, its data flow, and the tasks that the operator must perform based upon the information provided by the displays. System organization is best represented on the display in the form of simplified block diagrams. Overall system readiness can be seen at a glance in a top level system status display such as is shown for a typical TT&C station in Figure 3. The menu shown in the display window at the right hand side shows the operator choices of lower level displays which correspond to the major blocks of the system block diagram. Status data at this level is only "go/no-go" to provide the operator with a convenient summary of the system readiness and any existing subsystem faults. Each block in the summary display is associated with one or more detailed diagram and status displays for the associated subsystem, for example, uplink, downlink or antenna. These can be arranged in a hierarchical structure which lead the operator in an orderly fashion to the identification of a failed LRU. Some lower level displays also aid fault isolation by providing graphic information as to the current points of test signal insertion and signal monitoring. The test selections available replace the display menu when test mode is entered. Figures 4 and 5 show examples of subsystem level test mode and detailed equipment level operational mode displays.

Finally, focusing the operators attention on critical information is accomplished by two means. First, a dedicated area of every display format is devoted to current alarm conditions. Second, off-normal status indications within the main display can be highlighted to attract the operators attention. Highlighting can be accomplished on monochrome displays using effects such as blinking, reversed video, and varying intensity. If a color display is used, color coding can be used to provide even better visual attention focusing effects.

Interactive Techniques – The methods used within the software to combine display techniques with the use of the available input devices determine the level of effectiveness of the human/machine interface. The critical factors in providing an effective HMI are:

> **Control** –
> The operator must always perceive the system as a tool rather than the master. It is important for the system to include logic which can condense status and configuration information to identify a set of potential next actions in a situation, but the choice is best left to the operator.

Economy of input –
Since the opportunity for error increases with the number of input keystrokes required, interactions should make maximum use of single-keystroke techniques. Fixed and variable function keys and menu selection are favored for reduction of input keystroke requirements.

Adaptation to operator skill level –
Where forms fillin is required, the operator should have the option to include field constraint displays with each field. For example, an inexperienced operator may wish to be reminded of the valid entries in a field as shown below:

BIT RATE: __ K BPS (1,2 OR 10)

The more experienced operator may prefer a less cluttered display and wish the field to be solicited as follows:

BIT RATE: __ K BPS

Default options –
Where defaults are defined, they should be filled in when a field is initially displayed so that the operator need only signal acceptance by a single key entry. The ability to change defaults as experience is gained with the system or on a vehicle basis is very desirable.

Consistency –
Separate applications areas within the system should use the same human/machine dialog techniques (4). The techniques used by configuration control and test functions must not confront the operator with inconsistent responses or input requirements.

Responsiveness –
Every operator input must be acknowledged in a timely manner. Studies have shown that response delays exceeding two seconds degrade the operators effectiveness perceptibly. If an input action requires significantly longer processing time, the system must provide an interim response which lets the operator know that the input has been accepted and is being processed. Responses to operator errors must be messages which have meaning to the operator in the context of the operator skill level and training received. For example, if the operator misspells a file name, a message such as

UNRECOGNIZED FILE NAME

provides much more useful information than a more cryptic message such as

FILE SYSTEM ERROR CODE 0578.

On-line Tutorial Assistance –
One of the fixed function keys should be labeled “HELP” and the system should provide at least one level of “HELP” message at each state of the operator dialogue. These messages must not be cryptic message codes which the operator is required to look up in some reference manual. The time critical nature of the operator’s tasks require minimal dependence upon such reference material. In order to adapt “HELP” features to variations in experience levels, operators can be provided with a means of setting a “brevity” option in order to control the level of detail offered by the “HELP” function. The ability to refine these messages without extensive software changes is an important consideration in the design of the interactive software.

SOFTWARE DESIGN AND IMPLEMENTATION TECHNIQUES

One principle which must be applied throughout the design of the operator interaction for all system functions is best described as complexity management. This begins in the system design phase with the selection of LRUs which allow the system functional structure to be easily grasped and effectively displayed in block diagram form. The display hierarchy which results will have a manageable number of levels and will reinforce the operator’s understanding of the system functions and data flow (1).

The early stages of the TT&C control and display software design should involve a team with members from human engineering, hardware and software engineering and the operational organization. While the design process proceeds in a “top-down” fashion, its goal is to identify a set of elemental functions or “primitives” which constitute the lower level building blocks of the interactive display and test software to be developed. These primitives can be defined to perform very distinct general functions in each of the application categories required. The requirements of C&M for a TT&C station suggest the following categories:

Display primitives –
Status display field conversions (internal binary to displayed numeric, numeric to keyword conversion, etc.) and similar operations for displaying configuration information can support either normal operations or interactive testing.

Operator input processing primitives –
The dialog with the operator can be defined in terms of input validation and processing primitives which include syntactic checking, error and "HELP" message generation, display selection, test initiation and equipment control actions.

Control and status conversion primitives –
The conversion of input control commands from the master station to the equivalent station control commands, and the conversion and formatting of station status for messages to be sent to the master station can be defined in terms of primitive operations similar to display primitives.

Fault detection and alarm generation primitives –
This is the most difficult and the most critical area in the definition of interactive software requirements. The problem is determining when a status indication or combination of several indications is a transient condition which the system is merely required to report to the operator (warning level), and when such indications represent a fault condition (alarm level) and require immediate operator action to return the system to proper operation. A set of primitives is needed which can logically combine related status indications, and if required, measure durations of the conditions to resolve the indications to the level of operator attention needed.

Test Primitives –
The sequence of steps which define a test scenario lead to definition of test primitives. Test functions can use display, operator input processing and control primitives mentioned above but testing may require special functions such as time delays between control and monitor steps and the switching of test signal generation and monitoring equipment.

Once the process of defining the primitives has been accomplished, configuration and status displays, operator interactions, control and status conversions, and test scenarios can be defined as sequences of these primitive operations. These sequences can be encoded as data and stored in files which are read in when needed and interpreted in real time. This table-driven approach offers the flexibility needed in the definition of the processes while the development effort proceeds, and more importantly, during the operational phase. For example, driver table changes which modify the form or content of a display are far less likely to introduce software failures or unfortunate interactions than are corresponding changes in more traditional in-line code implementations of display functions.

Another benefit of the table-driven approach is that the tabular representation of a primitive sequence to perform a function generally consumes less memory space than equivalent in-line code to invoke the same program functions. The corresponding saving in memory is multiplied by the number of such invocations required in the processing sequence. The overall result is smaller program size and correspondingly reduced software complexity.

The table-driven approach has been used successfully for many years, but generally has not attained the levels of flexibility and ease of modification which should result from the technique. The challenge remains to develop tools for building driver tables for various processes without substituting data base generation complexity for program complexity. The likely candidate approaches include special dialogue specification languages, and interactive definition techniques. Specification languages have been used with some success (4), but share the disadvantage often associated with computer programming languages, that is, the need for special expertise. Machine-guided interactive methods can be implemented and tailored using application-specific menus and forms for soliciting dialogue sequences and amplifying data from the designer with minimum requirement for software expertise.

CONCLUSIONS

The progressive automation of TT&C stations requires increased care in the design and implementation of the operator interfaces with the station control and monitoring equipment. Effective systems must be designed from inception with critical operator tasks and information needs as design drivers. Interactive techniques must help the operator in learning the system, in determining subtasks to be performed, and must aid in the error-free accomplishment of all subtasks. The evolution of the system design from the start of a project to initial operation (and beyond) often requires many refinements and even major changes in the operator interface. A table-driven approach can provide the needed flexibility and extensibility. Development of interactive tools which help in the translation of operator dialogue specification into data base tables for use by the operational software are needed to enhance the cost effectiveness of table-driven techniques. Such tools, used in conjunction with a supporting dialogue and display simulation or prototyping system, will greatly improve the effectiveness of the human/machine interface design and implementation process.

REFERENCES

1. Brown, James W., “Controlling the Complexity of Menu Networks”, COMMUNICATIONS OF THE ACM, Vol. 25, No. 7, July 1982, pp. 412-418.

2. Clark, I. A., “Software Simulation as a Tool for Usable Product Design”, IBM SYSTEMS JOURNAL, Vol. 20, No. 3, 1981, pp. 272-293.

3. Hirsch, R. S., “Procedures of the Human Factors Center at San Jose”, IBM SYSTEMS JOURNAL, Vol. 20, No. 2, 1981, pp. 123-171.

4. Kasik, David, “A User Interface Management System”, COMPUTER GRAPHICS, Vol. 16, No. 3, SIGGRAPH ’82 Conference Proceedings, pp. 99-105.

5. Martin, James, DESIGN OF MAN-COMPUTER DIALOGUES, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1973, pp. 309-332, 361-369, 449-451.

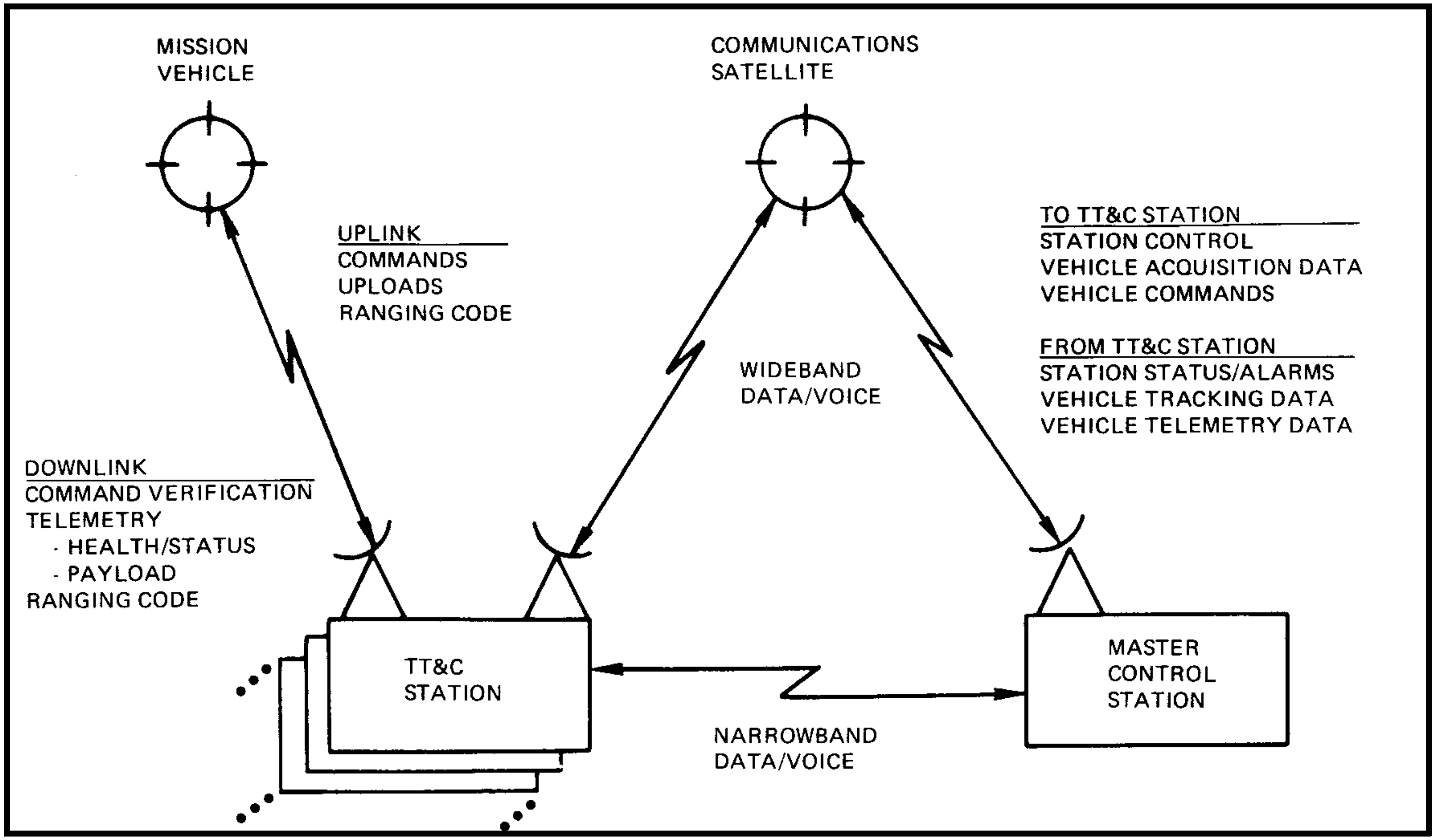

Figure 1. Typical Satellite TT&C Support Network

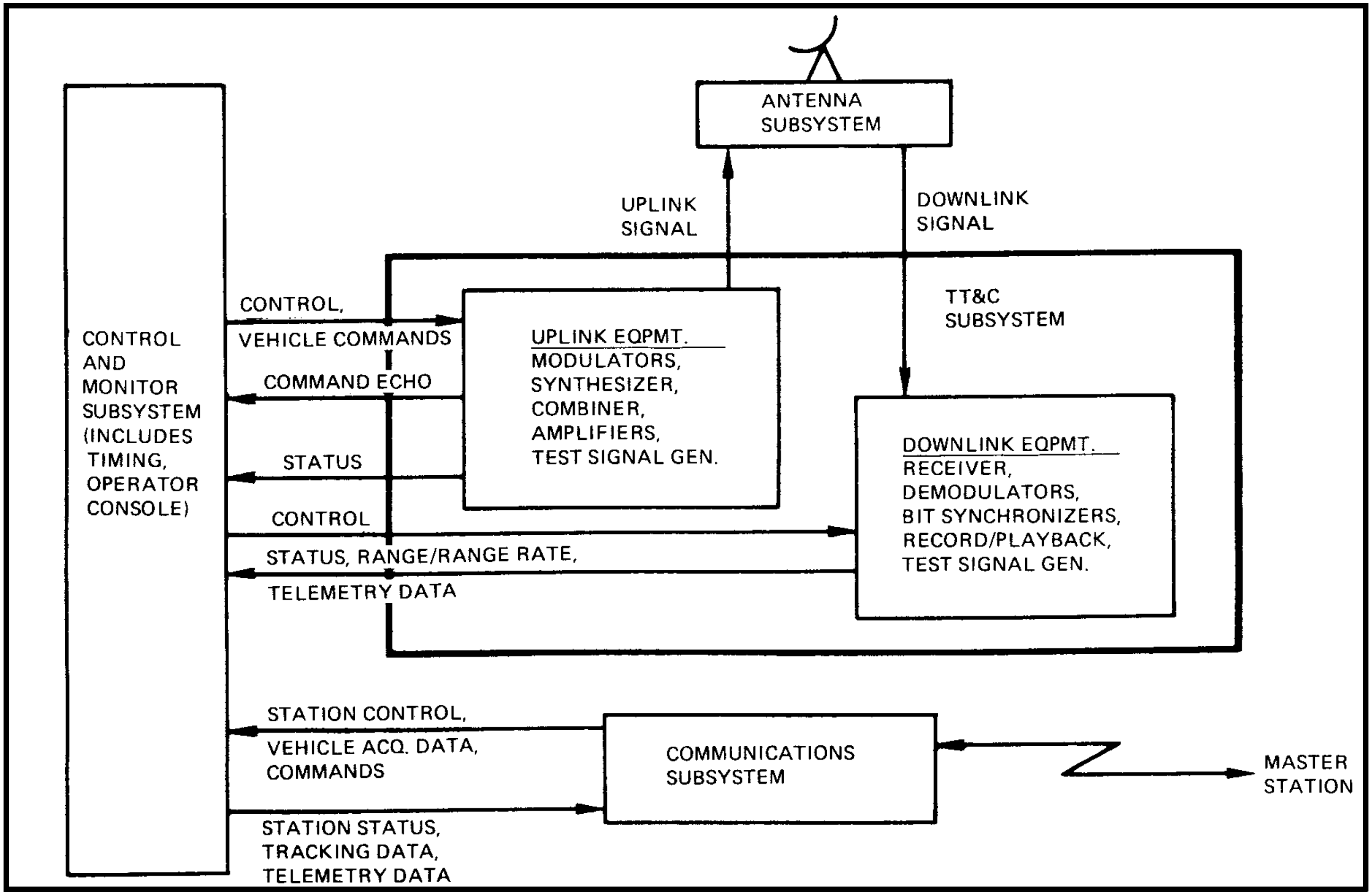

Figure 2. Typical TT&C Station Configuration

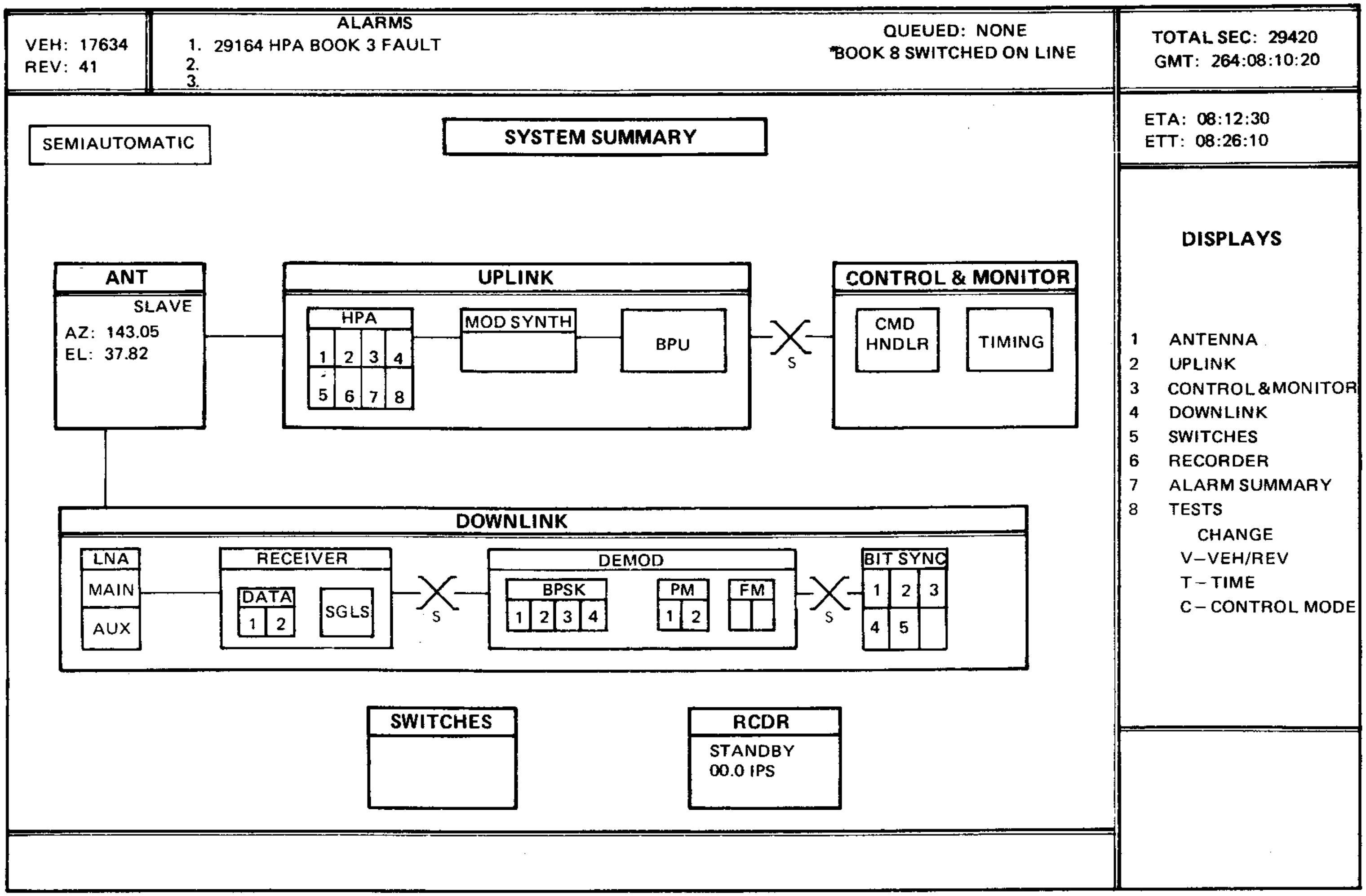

Figure 3. System Top Level Status Display

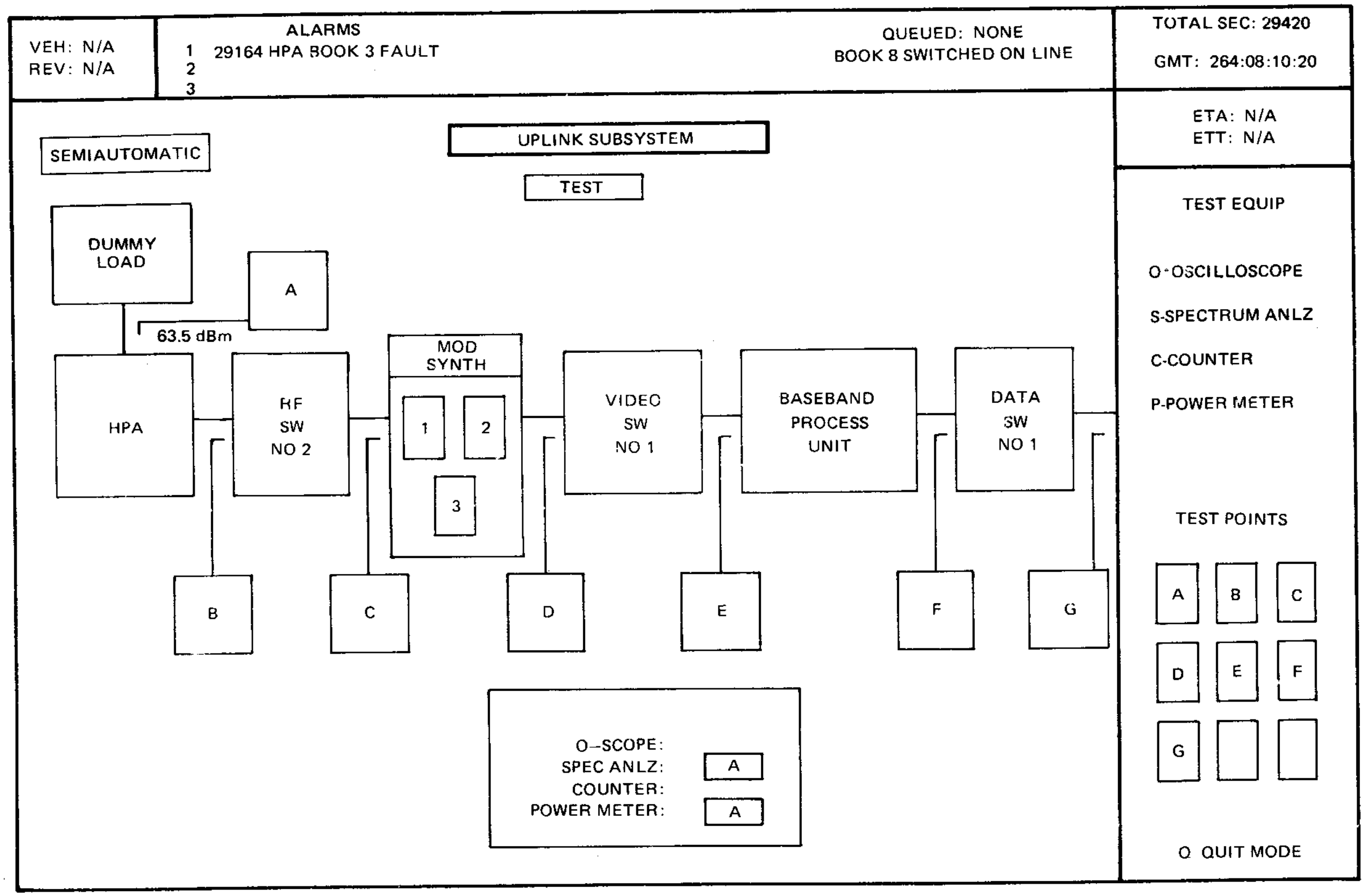

Figure 4. Subsystem Level Display-Test Mode

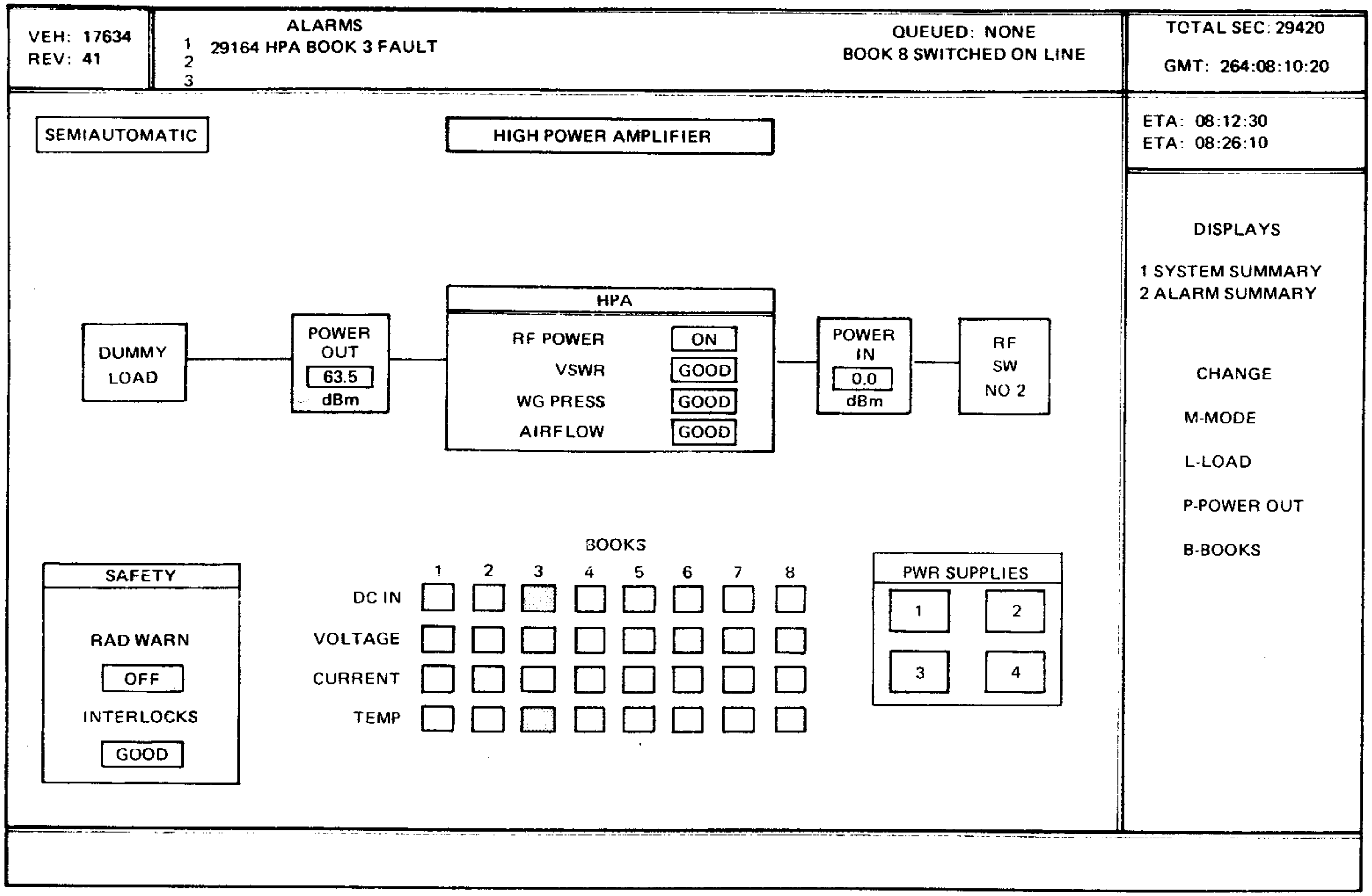

Figure 5. Detailed Equipment Display-Operations Mode