A Spacelab Principal Investigator's Guidance for Planning Scientific Experiments Using the Shuttle

Stanley D. Shawhan*
The University of Iowa, Iowa City, Iowa

Experience gained in defining and developing the payload and the mission timeline for the OSS-1, Spacelab-1, and Spacelab-2 missions suggests several areas which require careful planning to carry out a Shuttle scientific experiment. During the experiment definition phase early attention should be given to the thermal design, the analysis of potential safety hazards, and contamination since these areas can escalate the instrument design. In completing the Experiment Requirements Document it is important to be realistic in specifying the requirements and desires for mass, energy, data, orbit and attitude, and crew time but to be flexible in how these requirements are satisfied. Examples of resource allocations for Spacelab-1 and Spacelab-2 are given. To optimize the scientific return from a mission it is suggested that joint operations of complementary and compatible experiments be planned from the beginning to maximize the use of the limited resources. Crew members should be given primarily tasks of essential commanding and data interpretation; the experiment computer use should be limited to servicing the dedicated experiment processors and providing essential onboard commands and displays. It may be desirable to rely on experiment ground support equipment for essential data capture and processing rather than on the Payload Operations Control Center data services.

Introduction

THE advent of the Space Transportation System (STS) offers the first possibility to deploy and return scientific instrumentation from the near Earth orbit.[1] Instrumentation is placed above the obscuring lower atmosphere and into a high vacuum, low acceleration environment at the lower edge of geospace in the midst of a variety of solar-terrestrial processes within a region suitable for active plasma-particle-wave-photon experimentation.

Instrumentation can be accommodated in small standard containers of the "Get-Away Special" (GAS) program, housed in the crew storage lockers, rack-mounted at the aft-flight-deck or hard-mounted to the Orbiter structure within the payload bay. Items within the bay can be detached and articulated to distances of 50 ft using the Remote Manipulator System (RMS). Large or complex instrumentation and facilities can be most conveniently accommodated by the European Space Agency's (ESA) Spacelab system[1,2] with components including a manned module, pallets, and an Instrument Pointing System (IPS) along with associated remote acquisition units (RAUs), experiment computer (EC), cold plates and freon cooling loop, power distribution unit, and data display unit (DDU).

A unique feature of the STS is that crew space is available to carry not only the members required to position the Orbiter in orbit and attitude but also mission specialists and payload specialists who have the skills to operate the instrumentation and associated flight support equipment in order to maximize the results from a particular mission. The command and data systems on the Orbiter allow for man-in-the-loop operation and the high rate data link to the Payload Operations Control Center (POCC) allows for the investigation team to also be included in the loop in nearly real time. With the possibility of several missions to carry out a scientific program the hardware, software, and techniques can evolve based on on-orbit performance as well as on careful analysis of data between missions.

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*Professor of Physics, Department of Physics and Astronomy.

Although the prospects for experimentation on the Orbiter look bright, the experience being gained during the definition and development of instruments and timelines for the OSS-1,[3] Spacelab-1,[4] and Spacelab-2[5] missions indicates that some design areas and resource constraints need careful consideration in order to accomplish the scientific objectives. The point of this paper is to identify these design areas and limited resources and to suggest schemes by which scientific experiments can be planned and executed to obtain the desired data within these constraints.

For the discussion that follows, the Spacelab-1 and Spacelab-2 missions are used as representative of science-dedicated missions. They are important models because they do utilize the selection, funding, management, development, mission operations, and data analysis philosophies and procedures that are intended for Spacelab missions of the future. The Spacelab-1 mission[4,6] utilizes the Spacelab manned-module and a pallet of instruments to accommodate 38 instruments from ESA and NASA investigators. Spacelab-2[5,7] uses the Instrument Pointing System, three instrument pallets, and a special support structure. The remote Manipulator System is used to deploy a subsatellite. Both missions are to carry out investigations in the areas of physics, life sciences, astrophysics, and applications sciences.

Spacelab Experiment Allocations

The Spacelab system allows for the accommodation of a large variety of scientific instrumentation with a minimum of interface complexity and, consequently, for the rapid interchange of instrumentation between Spacelab missions.[1,2] Also, the command and data handling systems are particularly designed to accommodate the crew in the loop for nominal or contingency operations. However, the resources available to the payload for science must also support this Spacelab system.

Some of the primary resources which are allocated to the Spacelab payload in general and the percent of the allocation which is dedicated to the Spacelab-1 and Spacelab-2 experiments themselves are listed in Table 1. The total payload mass is limited by the maximum landing weight. Experiments on Spacelab-2 are allocated a larger portion—32%—compared to Spacelab-1 because of the additional Spacelab-1 weight for the module and support equipment. Both the power and the energy allocations are determined by the capability of a single fuel cell. In the case of Spacelab-2, most of the experiments could be run simultaneously for the entire mission from a power and energy standpoint. The Spacelab overhead is ~80% of the energy. For Spacelab-1 the module increases the overhead to ~90%. Instruments on Spacelab-1 must have a lower duty cycle because the peak experiment power exceeds the available power (119%), not including the overhead. One of the big uncertainties in the power usage and energy budget is the instrument heater requirements. Several Orbiter flights are required to test the thermal models to establish the heater duty cycles.

Low digital data rates can be handled through the Spacelab RAUs by the experiment computer.[1,2] However, the bulk of the digital data is handled through the high rate multiplexer (HRM).[1,2] Neither the Spacelab-1 nor Spacelab-2 peak data rates approach the 32 Mbps capability of this channel. As the maximum rate is approached the data recording onboard and on the ground as well as the downlink scheduling become significant problems. Experiment commanding and onboard data displays as well as servicing of dedicated experiment processors (DEP) can be handled by the experiment computer operations software (ECOS) which requires ~44 kbytes of the 65 kbytes EC memory. Any special DEP or analysis or control programs are routines in the 20 kbytes experiment computer applications software (ECAS) of which 60% and 70% are allocated to Spacelab-1 and Spacelab-2, respectively. The balance of ECAS is for crew use.

Propellant is required to create or negate "g" loads, to change orbit, and to track specific targets. In order to accomplish objectives requiring orbit or attitude adjustment, approximately 50% of the propellant is available for experiment use including attitude maneuvering for data dumps to the Tracking and Data Relay Satellite System (TDRSS). The balance is used for orbit insertion and for deorbit. Given the energy and propellant constraints and the occurrence of appropriate observing conditions, the prime observing time for an experiment can be determined. For a seven-day mission approximately 152 h are available. For Spacelab-2, 567 h are allocated as prime time or 371% of that available—meaning that almost four experiments can be conducted simultaneously through a mixture of crew and POCC control. Spacelab-1 has many more experiments and most of these operate for the duration of the mission with very little crew attention so nearly 15 experiments can operate simultaneously. Since two scientific crews are available each shift—8 h for the mission specialists and 10 h for the payload specialists—252 h of dedicated crew time is possible. For Spacelab-1 and Spacelab-2, ~65% is assigned to specific experiments with the balance used to monitor other experiments and to carry out other payload duties. Even if energy and propellant were available, the dedicated crew time limits the optimization of results from the man-in-the-loop operations.

A listing of the Spacelab-2 experiments and a detailed breakdown of the resources are given in Table 2. Mass values range up to 2000 kg for the experiment 6 cosmic ray telescope, which is a specialized structure instead of a pallet. Power

Table 1 Spacelab resource allocation to experiments

	Spacelab allocation	Spacelab-1 experiments[6]	Spacelab-2 experiments[7]
Mass	14,515 kg	2784 (19%)	4637 (32%)
Power	Average 7 kW	0.7 (10%)	1.3 (19%)
	Peak 12 kW	14.3 (119%)	2.6 (32%)
Energy	~900 kWh	100 (11%)	199 (22%)
HRM data	Peak 32 Mbps	4.7 (15%)	2.5 (8%)
Experiment computer memory for ECAS	~20 kbytes	12 (60%)	14 (70%)
On-orbit propellant	~7400 lb	3457 (47%)	3957 (53%)
Prime observing time	152 h	2248 (1479%)	567 (371%)
Dedicated crew time	252 h	177 (70%)	150 (60%)

Table 2 Spacelab-2 experiment resources utilization[7]

Experiment No.		Mass, kg	Average power, W	Energy, kWh	Maximum HRM data rate, Kbps	ECAS memory, kbytes	Prime time, h	Dedicated crew time, h
1	Vitamin D. Metabolites and bone demineralization	32	0	0	0	0	9	12
2	The interaction of oxygen and gravity influenced lignification	24	52	9	0	0	166	3
3	Ejectable plasma diagnostics package	372	34	5	333	0	19	48
4	Plasma holes for ionospheric and radio astronomy studies	0	0	0	0	0	7	7
5	Small helium-cooled i.r. telescope	770	101	15	614	2.0	27	Monitor
6	Elemental composition and energy spectra of cosmic ray nuclei	1968	232	33	102	1.25	137	Monitor
7	Hard X-ray imaging of clusters of galaxies and other extended X-ray sources	570	179	25	64	2.2	103	Monitor
8	Solar magnetic and velocity field measurements system	198	150	22	1365 (video)	1.9	18	
9	Solar coronal helium abundance Spacelab experiment (chase)	100	74	12	8	2.0	15	79
10	Solar u.v. high resolution telescope and spectrograph	256	325	47	(RAU) (video)	2.6	16	
11	Solar u.v. spectral irradiance monitor	83	95	14	(RAU)	1.5	4	
12	In-orbit calibration of mesa low *g* accelerometer	15	20	3	(RAU)	0.2	23	Monitor
13	Properties of superfluid helium in zero *g*	250	93	14	20	0.35	23	Monitor
	Total	4637	1355	199	2506	14.0	567	150
	"Average" experiment	357	104	15	193	1.1	44	12

values range up to 325 W with an energy allocation of 47 kWh for experiment 10 on the IPS. Maximum HRM data rates of 1365 kbps occur for experiment 8 in addition to the use of the 4.5 MHz video downlink. Experiment 10 utilizes 2.6 kbytes of the 14 kbytes of ECAS memory. Both experiment 2 and experiment 6 are allocated prime observing time for nearly the entire mission since very little crew intervention is required. However, experiment 3 and the solar experiments on the IPS (experiments 8-11) require more than one crew member to support the allocated prime time; for example, experiment 3 has 48 h of dedicated crew for 19 h of prime time indicating ~2.5 crews for the subsatellite deployment and fly-around operations. Values for an "average" Spacelab-2 experiment are given at the bottom of Table 2. These values may be representative of the future discipline-dedicated Spacelab payloads.

Experiment/Instrument Definition

Joint Operations

Experiments for the current OSS-1, Spacelab-1, -2, and -3 missions and the 38 experiments for possible future spacelabs were selected from proposals submitted in response to NASA Announcements of Opportunity. These experiments were proposed largely as stand-alone investigations without regard for other proposed complementary investigations. Joint experiment scenarios have subsequently been developed between investigation teams. For example, the vehicle charging and potential experiment and the plasma diagnostics package on OSS-1, the four solar experiments (experiments 8-11) on Spacelab-2, and the plasma holes (experiment 4) and plasma diagnostics package (experiment 3) on Spacelab-2 have defined joint functional objectives. These joint operations are particularly significant because they enhance the overall scientific output for the mission by providing complementary measurements and they minimize the various resources required to obtain these results. It is therefore important for the possibility of joint operations to be identified early in the experiment definition phase.

Experiment Requirements Document

Experiments are assigned for definition and development to any of the NASA Centers usually along discipline lines. Marshall Space Flight Center (MSFC) has the responsibility to accommodate the experiment into a spacelab once the investigation has been assigned to a particular mission. During the definition and development phase an Experiment Requirements Document[8] (ERD or equivalent) is prepared which specifies the requirements in terms of resources, pointing accuracy, orbit, special tests, ground operations, software, safety, POCC services, etc., that are necessary to complete the investigation. MSFC then carries out a physical and timeline accommodation study including all the experiments for that mission to maximize the number of requirements that can be satisfied, and this information is collected in the Integrated Payload Requirements Document (IPRD).[6,7] After some iteration the Instrument Interface Agreement (IIA)[9] is created.

In preparing and iterating the ERD it is important to establish requirements that are consistent with the original proposal, in line with the resources available as indicated in Tables 1 and 2, commensurate with the Orbiter performance characteristics, and include scenarios for joint operations. Firm requirements must be clearly distinguished from desired performance. Suggestions for meeting a particular requirement are appropriate but the suggestions should be written so they are not interpreted as the requirements themselves.

Design Analyses

Three areas related to the instrument design have required particular attention for instruments developed for OSS-1, Spacelab-1, and Spacelab-2: thermal control, safety hazard analysis, and contamination control. Thermal control is a particular problem because the Orbiter bay can be oriented toward or away from the sun for extended periods of time which allows the pallet-mounted equipment to become very hot or very cold. On pallets, instrumentation can be mounted on cold plates connected to a freon loop with a large heat capacity and a radiator system. However, in the hot case the radiator system is the least efficient. Within the module, equipment is forced air cooled. Also, the equipment should be able to survive the hot and cold extremes of a contingency situation if the freon loop or forced air were to fail. The thermal design has been particularly difficult for the Spacelab-2 experiment 3 plasma diagnostics package which has to operate in the bay without a cold plate, on the RMS, and as a satellite. Also, instruments mounted on the IPS must maintain thermal control without cold plates. To date thermal design parameters have been changing as the payload thermal analyses evolve.[1,6,7] After several STS flights, the thermal modeling should be more realistic so that thermal control techniques can be more readily specified.

Rigid safety criteria have been established to protect the ground crews during payload integration and the flight crew during the mission.[10] Of particular concern have been the stress on mechanical structures and the flammability and outgassing of nonmetallic materials. Stress due to launch and landing loads and stress corrosion have been addressed in detail in Sec. 14.0 of the IPRD,[6,7] for example. Flammability during ground operations and toxic outgassing are stringently controlled through the selection of materials.[11] Another criteria is that the experiment ground support equipment (EGSE) must undergo both a mechanical and an electrical safety analysis to protect both the flight hardware and the ground crews, particularly at the Kennedy Space Center (KSC). Consideration of these safety issues has meant that techniques and materials that have been acceptable in other space programs are not necessarily acceptable for STS hardware. Obviously, these issues must be identified early in order to comply with the safety criteria and to keep the instrument cost reasonable.

Finally, the area of contamination due to gaseous and particulate matter is of particular concern to instruments with optical surfaces. These restrictions have been imposed by the Investigator Working Group itself for Spacelab-2 as appropriate for the particular complement of instruments. As a result of these contamination limits, additional restrictions on materials, thermal control surfaces, and instrument purges may be applied.

Mission Timeline

The mission timeline for 84-96 h mission elapsed time (MET) for Spacelab-2 is shown in Fig. 1 to give an overall feel for the many factors that must be taken into account in the timeline accommodations. During this 12 h crew timeline period the blue crew, consisting of a payload specialist (PS2) and a mission specialist (MS2), is active although there is a handover to the red crew at ~94 MET. For the active crew, the specific tasks fall into blocks of time from as short as 10 min to well over 1 h. The notation in each time block refers to a particular task (SPC1 = solar physics, MS2LU/PS2LU = lunch, PS2PSA/MS2PSA = sleep). A typical crew function flowchart is given in Fig. 2 to indicate the types of steps to be performed in a task and the interactions required with the DEP through the EC and with the investigator team in the POCC.

In defining the extent of crew involvement one must assess if the involvement is essential to the conduct of the experiment in terms of issuing critical commands or in terms of interpreting data displayed onboard in order to issue a sequence of commands to optimize the experiment or to take advantage of a "target-of-opportunity." Could the data be interpreted and commands issued just as easily from the POCC? A

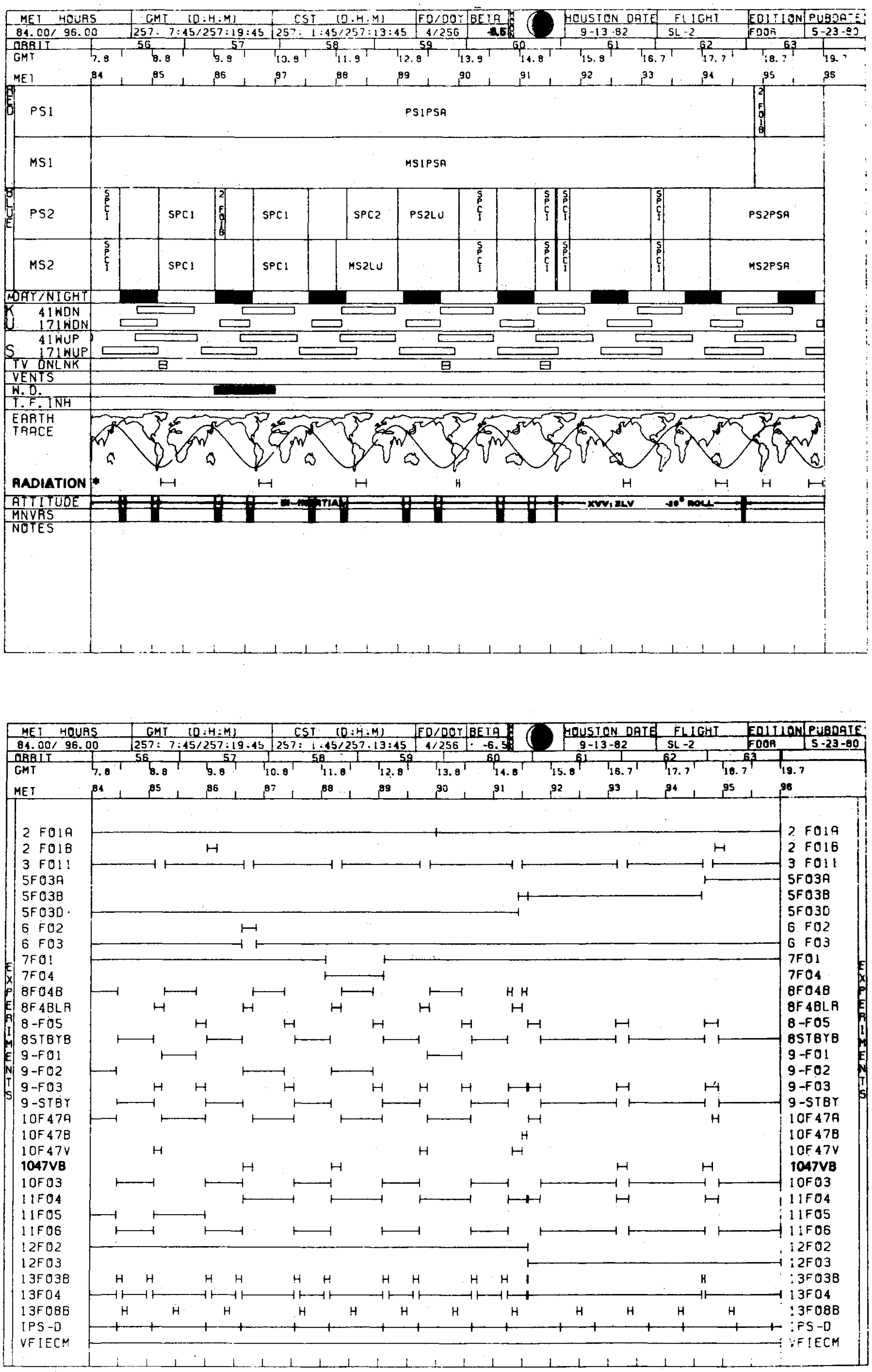

Fig. 1 Sample mission timeline from Spacelab-2 (Ref. 12).

significant crew involvement means that one or more crew members on each shift need to have the skills required to interpret the results from the instrument which in turn implies an extensive crew training program.

Data Link Timeline

Most of the science data comes via the Ku-band (KU) downlink. At the time of Spacelab-2 there will be only two TDRSS satellites so that the real-time coverage is limited to about 70%. For future Spacelab flights, three satellites will provide ~90% coverage so that the POCC can be considered in the loop.

Attitude Timeline

In order to satisfy a variety of attitude requirements for a number of instruments over the mission duration, the Spacelab-2 Orbiter is required to make a series of attitude maneuvers each orbit. A representative bi-inertial and +30 deg roll attitude is depicted in Fig. 3. Although it may be possible to develop an attitude timeline to obtain the required duration of specified look directions, the propellant budget indicated in Table 1 may be an overriding constraint. On Spacelab-2 there are engine firings to deposit large clouds of burn products to study the ionospheric effects (experiment 4), and there are orbit change maneuvers to fly around the subsatellite (experiment 3) and to gain altitude (experiment 7) in addition to attitude maneuvers.

Instrument Operation Timeline

During the period covered in Fig. 1, the crew is dedicated primarily to the operation of the four solar instruments on the IPS with some time available to take data for the plant growth units (experiment 2) at ~86 and ~95 MET (task 2F01B). This is an interesting time period in that all the onboard instrumentation (lead number identifies instrument) are operating simultaneously although most of them are undergoing automatic sequencing. The energy constraint does not allow simultaneous operation for the entire mission.

Timeline Replanning

It is unreasonable to think that the "final" mission timeline that is developed nearly a year before flight will be executed perfectly for the entire mission. Launch holds or delays, space motion sickness, instrument failure, inadequate task descriptions, etc., could all contribute to the modification of the timeline during the mission. For Spacelab-1 and Spacelab-2, MSFC has proposed a 12-h, replanning cycle which occurs continuously. Every 12 h, mission operations personnel meet to assess the status of the Orbiter and crew and to establish any mission constraints for the 12-h period in question. The investigators meet with the payload personnel to assess the status of the payload and the instruments. Any modifications to the planned timeline are proposed and the impacts are evaluated. The crew is then informed of the procedural changes. For any 12-h period, the goal is always to return to the nominal timeline.

In order to support this replanning activity, the investigator team must have enough personnel to staff at least two shifts each day. Also, contingency schemes should be planned including the command sequences that would be needed to be uploaded to the DEP from the POCC.

Command and Data Handling

Experiment Computer

The experiment computer is coupled to 1) the remote acquisition units to obtain data from instruments and to provide commands, 2) a digital display unit with a keyboard for initiating commands onboard and displaying processed RAU data, 3) a mass memory unit for memory/program exchange, and 4) the data link with the POCC.[1,2] A sample

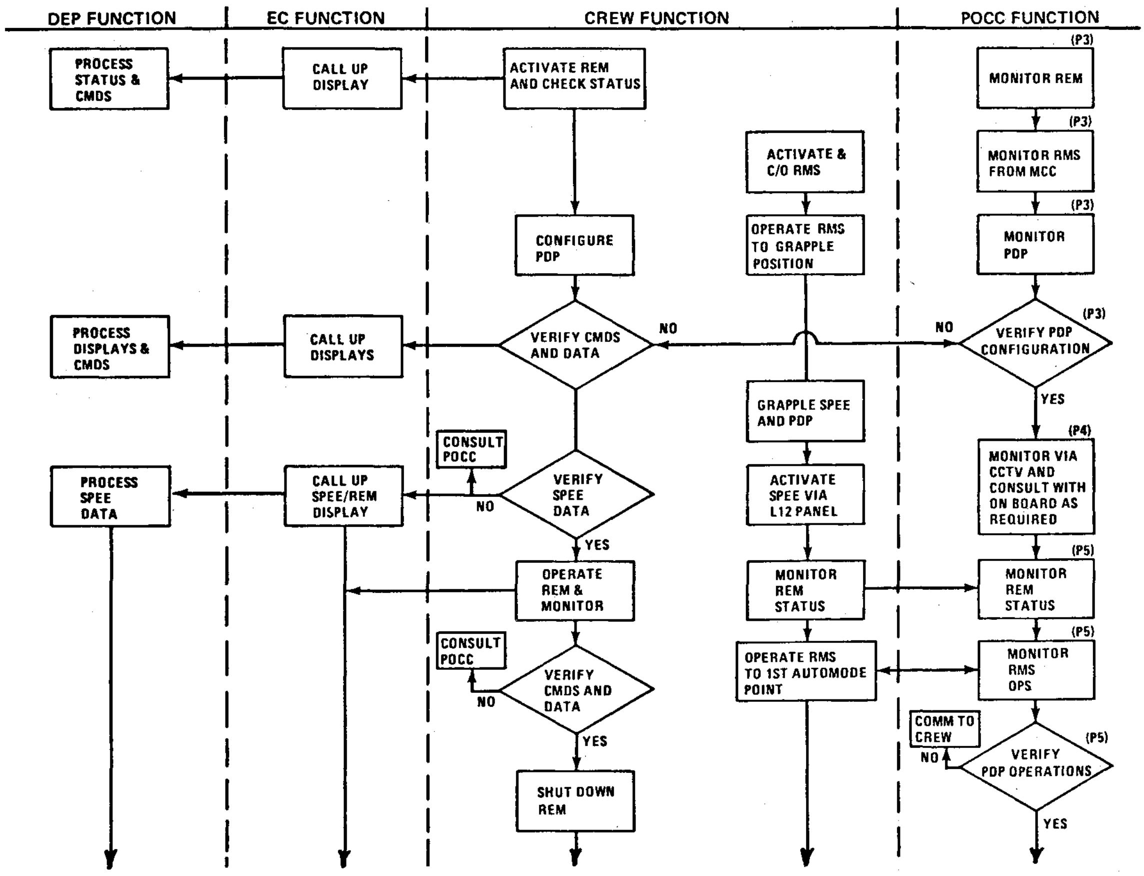

Fig. 2 Typical crew function flowchart.

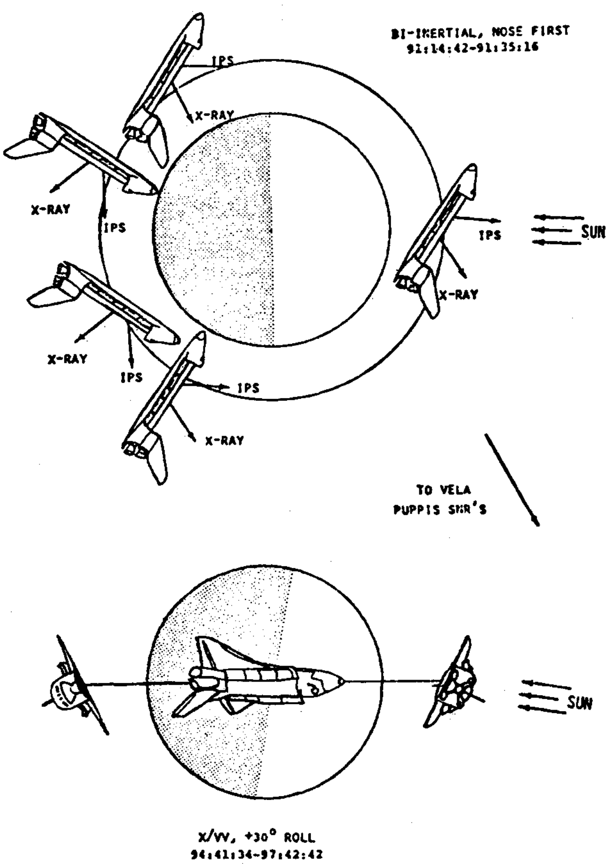

Fig. 3 Typical attitude maneuvers.

display from Spacelab-2 experiment 3 is shown in Fig. 4. This display contains item entry commands (items 1-24) which can be sent by two keystrokes since these commands are active only when the display is up and the commands are predefined. The remainder of the display contains housekeeping data for experiment 3. On Spacelab-2 there are ~500 item entries and ~50 displays which are supported by ECOS.

To build a discrete command at the keyboard it takes six keystrokes and to build a serial command it takes 13-20 keystrokes. Once a command is entered it takes ~1 s to execute. For commands issued from the POCC it takes 1-2 s for a single stage command (not checked on receipt) and ~12 s for a two-stage (checked) command if the uplink is established.

In controlling an instrument it is important to decide on the prime command scheme. Neither commands from the keyboard nor from the POCC can be counted on for quick reaction to a contingency situation. Keyboard item entry commands are the most efficient from the crew standpoint since they are predefined. Routine commanding from the POCC relieves the crew from having to call up a display and to send item entry commands, or from having to compose commands if they are not in response to some newly interpreted data or to a target-of-opportunity. A scheme which would minimize the crew time and ECOS/ECAS overhead is to store command sequences in the DEP. These sequences could be time-tagged or initiated by item entry. The item entry could also be used to fill limited data fields (to set parameter limits) within the DEP commands. All DEP command sequence updates could be handled from the POCC. The flexibility of rebuilding the instrument sequences is particularly important if the timeline is replanned during the mission.

Use of the mass memory unit (MMU) can expand the very limited EC core space in support of ECAS. However, the MMU has an access time of 2-30 S. Use of ECAS to handle DEP protocol, instrument control logic, and special processing of data to be displayed may be justified. However, one implementation problem lies in the inability to completely check the software before actual integration into the Orbiter just before launch, although simulators are available. It seems that unless the EC is upgraded, instruments should contain DEPs to handle any instrument-unique tasks such as instrument control logic and specialized displays not handled by ECOS. Also, the degree of data processing and display handled by ECOS should be kept to the minimum that the crew can reasonably use in order to minimize the number of loads from the MMU.

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30P  3 PDP OPERATIONS                              GMT 270/10:30:00

1  DISPLAY SEL [0]  0                          [40/60]    3EM
  BATT TEMP       32.4  C                PDP CURR       52 3MG
                                             VOLT       58 3WK
     2 BUS PWR       ON                      TEMP       51 3SP
EXP PWR     3ON      4OFF    ON               /SPEE TEMP 43
PDP PWR     5ON      6OFF    ON          SPEE TEMP      42
PDP HTR     7ENA     8INH   ENA              HTR ON/OF  99
REM HTR     9ENA    10INH   ENA          RDP CURR       52
PWR XFER   11BAT    12ORB   BAT              VOLT       53
PDP XMTR   13ON     14OFF    ON              TEMP       43
DAT MODE   15DIR     [0]                 REM TEMP       58
DIV COMB   16IN     [1]                      HTR ON/OF  99
RCVR SEL   17R1     [2]        1         EGF TEMP       47
           18R2     [3]
LEP PWR    19ON     20OFF    ON          R1 AGC [=R2]   78
IMS PWR    20ON     22OFF    ON          R2 SGC [=R1]   77
TIME       22RST    24RUN   RST          PRES [<50]     24
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Fig. 4 Sample Spacelab-2 display.

Analog Data

Some types of experiments produce moderate bandwidth analog data that are not really efficiently handled by an analog-digital conversion and the HRM digital link or by the 4.5 MHz CCTV downlink (when it is available). Two such services are slow-scan TV images from optical experiments and electromagnetic wave data from space plasma wave instruments (~50 kHz). Future developments of Spacelab should accommodate these types of data.

POCC Operations

Each experiment is provided with a user area in the POCC which includes a console for initiating commands to the user's instrument and for displaying and capturing any parameters from the Orbiter instrumentation (OI) or experiment computer input/output (ECIO) data stream. HRM data are delivered as they are inputted to the Spacelab. All of the downlinked data including the OI, ECIO, HRM, and CCTV (analog) are captured for nearly realtime playback and for later processing onto computer compatible tapes as may be specified.[1] The POCC provides very limited capability, however, for processing the HRM data. The trend seems to be to provide EGSE in the POCC which is adequate for capturing and processing HRM instrument data. These EGSE data systems almost have to exist anyway in order to conduct instrument-level tests before and after integration into the Spacelab.

Summary

Through development of instruments for the OSS-1 and Spacelab-2 missions, various opinions have been developed about the capabilities and the limitations of the STS for the conduct of scientific experiments. Implications of the STS design requirements and resource allocations have been discussed as they apply to the experiment/instrument definition, to the mission timeline, and to command and data handling. For these areas, approaches have been suggested to maximize the capability to meet the scientific objects which should be considered as a scientific experiment is being planned and as the Spacelab is upgraded for future missions.

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