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RECOMMENDATIONS FOR THE DESIGN AND OPERATION OF THREE-AXIS STABILIZED SPACECRAFT, BASED ON A CRITIQUE OF CTS/HERMES ON-ORBIT OPERATIONS

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*The opinions expressed in this report are those of the authors who are solely responsible for all comments and recommendations.*


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# 1.0 BACKGROUND

## 1.1 The CTS/Hermes Program

The Communications Technology Satellite (CTS), named Hermes, was an experimental geostationary communications satellite, that was launched 17 January 1976, as a joint program of the Canadian Department of Communications, and the United States National Aeronautics and Space Administration. The European Space Research Organization (now the European Space Agency) was also a participant.

The three-axis stabilized satellite was designed and built in Canada; NASA supplied several spacecraft components (including the 200W TWT, with its power conditioning and thermal control hardware), the launch vehicle, and environmental test and operational support; ESA also provided several spacecraft components (including the 20W TWT's, experimental array electronics, and a parametric amplifier), and developed the blanket and solar cells used in the deployable solar arrays.

CTS/Hermes program management was provided by the Space Communications Program Office at the Communications Research Centre in Ottawa, Canada. The satellite was operated and controlled from the Spacecraft Ground Control Centre at CRC, with support from the NASA STDN network when necessary. This support became critically important late in life due to major problems with the satellite telemetry transmitter. Use of the satellite for communications experiments was shared equally between NASA and DOC (alternating daily) until June 1979; Canada then continued with demonstrations and experiments until the end of the mission.

The satellite ceased operation (due to a compounding of several spacecraft problems) in November 1979, after almost doubling its nominal design life of two years. The final spacecraft configuration was essentially that planned for shutdown at the end of the mission, which had been scheduled for January 1980.

For conciseness, this report assumes familiarity with the CTS/Hermes program through the references and the sources listed in them.

## 1.2 Program Objectives and Achievements

CTS/Hermes had a higher radiated power capability (boresight EIRP of 59 dBw on one channel) than any other satellite launched to date, and was one of the first spacecraft to operate in the 12/14 GHz range. It is regarded as the forerunner of satellites that are expected to provide a wide range of expanded communications services in the next decade.

The basic objectives of the CTS/Hermes program were:

a) To develop and flight test the space hardware necessary to provide an accurately positioned, high power, high frequency communications signal.

b) To measure and evaluate the characteristics and capabilities of communications using this type of signal (including the use of small, low-cost, transportable ground terminals).

c) To demonstrate, test and evaluate the use of satellite communications for various social and scientific purposes, particularly where feasibility was significantly enhanced by the signal characteristics mentioned in a) above.

More details on the program objectives, and on the methods applied to achieve them, are given in References 1 and 2.

In meeting all of these objectives, the program was extremely successful, and the overall performance of the total system (satellite, ground station, ground terminals, and personnel) was of very high quality throughout the mission.
This success is attested to by:

a) The satellite remained fully operational for almost twice its nominal design life-time of two years.

b) Demand for use of the satellite by experimenters remained high throughout the extended mission.

c) Virtually all of the originally planned experiments were successfully completed, along with many that were added when the mission was extended.

d) Significant resources are being committed, in both the United States and Canada, to develop future operational services based on the CTS/Hermes experience.

## 1.3 Purpose and Scope of this Report

A large body of documentation already exists on all aspects of the CTS/Hermes program. In particular, References 1 and 4 and the sources listed therein provide a detailed picture of the satellite, ground station, ground terminals, and operations.
References 2 and 4 and their associated sources cover the scope and substance of the social and technological impacts of the program. The overall success of the program is clearly demonstrated, and a great deal of information of use in further developing satellite communications technology is included.

Given the successful nature of the mission, the existing documentation is largely concerned with the positive aspects of the various parts of the program. However, any complex, technically advanced system will inevitably have problems; on the CTS/Hermes program, these ranged from minor inefficiencies in operations to the final loss of the system. In retrospect, and with information and knowledge now available, certain features of the design and operation of CTS/Hermes could have been improved upon. The lessons to be learned from these aspects can be extremely useful in future projects, but tend to be underemphasized in most analyses, due primarily to the overwhelming preponderance of positive data.

This report documents comments and recommendations derived from a detailed critique of CTS/Hermes on-orbit operations. The areas covered include the overall spacecraft operations system; spacecraft hardware, ground control station hardware and software, and off-line hardware and software. Communications experiments and ground terminals, and the aspects of NASA STDN support that were peculiar to CTS/Hermes are specifically excluded.

## 2.0 CTS/HERMES OPERATIONAL PROBLEMS

### 2.1 Data Gathering and Analysis

In order to develop the recommendations of Section 3 of this report, it was first necessary to identify those areas of CTS/Hermes on-orbit operations where there were significant problems and/or where significant improvements could have been made. This was accomplished by:

a) Reviewing existing documentation, including catalogues of anomalies, reports of discrepancies, logs of mission operations, and recordings of telemetered spacecraft data.

b) Consulting all available spacecraft and ground station operations personnel.

The information gathered was compiled into an itemized list of separately identifiable problems, and the list organized into subsets, each associated with a different subsystem (where "subsystem" includes spacecraft subsystems and a categorization of the other aspects of operations, e.g. Ottawa ground station computing hardware, etc.).

Each item on the list was then analyzed to provide brief descriptions of the problem, its causes (identified and postulated), and its consequences (realized and potential). Further analysis led to recommendations and/or comments associated with each item, generally indicating how problems could have been avoided, and improvements made, in CTS/Hermes operations.

### 2.2 Limitations on Data Gathering

While every effort was made to be accurate and complete in the work described in Section 2.1 of this report, there were some constraints, including:

a) Time and manpower were severely limited.

b) Documentation was generally inadequate.
While Reference 3 was an invaluable source of data on spacecraft hardware anomalies, no equivalent listing of problems in other areas existed, and extracting information from the general documentation took an unacceptably long time.

c) Many of the individuals whose inputs would have been of most use were no longer available. In particular, subsystem level expertise (necessary to properly analyze the causes of problems, and to generate adequate recommendations for avoiding them) was significantly lacking.

d) By the end of the mission, or shortly thereafter, most of the operations personnel were fully committed to other programs. Under severe time constraints because of this, their inputs, while extremely useful, tended towards generalized, system-level comments and recommendations, rather than details on problems and their impacts.

The resulting over-dependence on the memories and opinions of a small number of individuals possibly compromises this report to some extent. Specifically:

a) Some subsystems are perhaps not covered as completely, or in as much detail, as others.

b) There may be a tendency to overemphasize problems that arose late in the mission (particularly those related to the telemetry degradation and to the final spacecraft loss), at the expense of the early stages.

## 2.3 Undesirable Operations Events and Spacecraft Anomalies

All of the information resulting from the work described in Section 2.1 of this report has been tabulated as a list of Undesirable Operations Events (UOE's) and Spacecraft Anomalies (SCA's). This table is attached as an Appendix.
It should be noted that:

a) In many cases, to avoid unnecessary repetition, several items have been grouped as a single entry, generally where the problems had common, or closely related, causes and/or consequences.

b) The break-down into problems/causes/consequences/recommendations is often somewhat arbitrary, particularly where the precise cause-effect relationship is uncertain.

c) Many problems impacted more than one subsystem, and thus are included several times in the table, with the emphasis, grouping (see a above), and break-down (see b above) varied to reflect the interests of the specific subsystems.

Despite the limitations described in Section 2.2 of this report, it is felt that the UOE/SCA list forms a reasonably complete critique of CTS/Hermes design (in terms of its operational impacts) and operations. On a subsystem by subsystem basis, the table provides a source of information on:

a) The difficulties and anomalies that occurred.

b) The significance of each problem, and the severity of its impact on operations.

c) The probable sources/causes of each problem.

Further details on some of the more significant problems can be found in the reports of several review boards (References 5-10).

While the list is based on, and directed towards, problems on CTS/Hermes, much of the information can be applied in other programs. In particular, many of the recommendations/comments can be used to identify the implications of CTS/Hermes operational problems in the design and operation of future spacecraft.

## 2.4 Summary of Problems

The problems that had the greatest impact on CTS/Hermes on-orbit operations were (in order of significance):

a) Telemetry transmitter problems (Reference 5).

b) NESA-A anomalies (Reference 6).

c) O/T impulse delivered after AFP trip (Reference 6).

d) Loss of battery capacity (Reference 1).

e) EPC-A failure (References 7 and 8).

f) Variable, degraded LTE performance (Reference 1).

g) Overheating of TEP OST (References 9 and 10).

The remainder of this section consists of a brief summary of all the more significant problems encountered in CTS/Hermes on-orbit operations. Details on these (and many others of less significance) are given in the Appendix. Note that many of the problems listed here would have been minor in isolation, but became major due to interaction with others (e.g. telemetry transmission beamwidth would have been adequate if both telemetry transmitters had operated at full power).

2.4.1 Telemetry transmitter problems (Tx A failed; Tx B severely degraded), with major impact on all aspects of operations.

2.4.2 Limited beamwidth telemetry transmission.

2.4.3 Non-redundant telemetry Encoders; inadequate telemetry in several areas.

2.4.4 Excessively complex command structure and sequences, particularly multiple function commands.

2.4.5 Variable, unpredictable, large-scale loss of battery capacity, and cell drop-outs.

2.4.6 Mismatch between batteries and between cells in each battery.

2.4.7 Excessively complex battery management required.

2.4.8 Battery UVS could not be completely disabled.

2.4.9 UVS trip was essentially catastrophic.

2.4.10 Loss of EPC-A.

2.4.11 Loss of 15% of experiments array power.

2.4.12 Body arrays kept H/K bus switch open (e.g. post-eclipse).

2.4.13 SPC-A trip-offs.

2.4.14 Loss of SATE and TEC.

2.4.15 NESA-A anomalies (turn-on and running).

2.4.16 Complex NESA-A management.

2.4.17 Excessive NESA cycling required.

2.4.18 O/T delivered impulse after AFP trip.

2.4.19 Attitude sensing inadequate for non-standard situations.

2.4.20 Resources (particularly manpower) insufficient for analysis of anomalies and work-arounds, and for developing, testing, and implementing previously unplanned major operations.

2.4.21 Unexpected attitude transients, wheel speed changes, and orbit effects, particularly during N-S S/K and move West.

2.4.22 Double dead-banding in roll-yaw.

2.4.23 Wheel speed operating range was too narrow; tachometer was too coarse.

2.4.24 Data/analysis on mass properties and alignment was inadequate, particularly regarding variations (daily, yearly and life-time).

2.4.25 Prime array orientation system was too complex; the backup approach was better, but design and test were not adequate for long-term use.

2.4.26 Array sun sensor fields of view were too narrow.

2.4.27 Variable, unpredictable, large-scale degradation in LTE performance; loss of one LTE.

2.4.28 Large uncertainties in fuel calculations.

2.4.29 Thruster preheat required excessive power and time.

2.4.30 Inadequate thermal telemetry; loss of several RCS telemetry parameters; badly placed sensors.

2.4.31 Excessively complex thermal control required (particularly for batteries and RCS).

2.4.32 Heaters very badly grouped (physically and by command structure); excessive heater cycling; temperature limits exceeded.

2.4.33 Satellite rapidly cooled below survival temperature when dissipation from internal components lost.

2.4.34 TEP OST overheated (due to heat-pipe freezing).

2.4.35 20W and 200W TWT trip-offs.

2.4.36 Losses of uplink and/or downlink lock (due to antenna updating, S/C anomalies, etc.).
Significant problems in reacquiring lock.

2.4.37 Inadequate documentation of all aspects of operations, including:

i) Cumbersome, unclear operating procedures and instructions.

ii) Lack of information on expected S/C behaviour (as opposed to specification/test limits).

iii) Lack of easily accessible S/C test and calibration data.

iv) Lack of information on ground-station equipment, and its configuration, calibration, etc.

v) Summaries of major occurrences, problems, and general operations were too generalized to be easily and directly usable for detailed operations analysis and planning.

2.4.38 Inaccurate and inflexible calibration system.

2.4.39 Slow, time-consuming, complex and inflexible off-line data processing.

2.4.40 On-line computers were too small and slow to allow S/W flexibility, and had inadequate I/O capability.

2.4.41 On-line S/W was inflexible, over-complex in some areas, and under-sophisticated in others.

2.4.42 Software was very susceptible to problems when TM data was bad.

2.4.43 On-line software, procedures, etc. were not ready at start of on-orbit operations.

2.4.44 No S/C switching model in ground station S/W.

2.4.45 Lack of interaction between testing and operations/software design and planning.

2.4.46 Operations personnel were inadequately trained.

2.4.47 Testing of procedures was inadequate.

2.4.48 NSP's were virtually non-existent at launch, and had to be improvised on-line to a large extent.

2.4.49 Real-time simulation was not available for on-orbit operations planning and training until well after launch, and there were significant problems in the use of the Sigma 9.

2.4.50 The off-line computer (Sigma 9) was relatively slow and core-limited; requirements of other users severely constrained its use for e.g. R.T.S., data processing, etc.

# 3.0 RECOMMENDATIONS FOR FUTURE SPACECRAFT

## 3.1 Introduction

The recommendations given as part of the Appendix are closely related to CTS/Hermes, and tend to be quite detailed; while useful guidelines can be drawn from them for application to the design and operation of other spacecraft, this section is an attempt to provide such guidelines in a more direct, less detailed, somewhat generalized form. No attempt is made to "weight" the recommendations - this can only be done by assessing the impact of the problems that generated them, as described in the Appendix.

It should be emphasized that these recommendations are derived directly from the Appendix, and thus are based on a fairly restricted data set. In particular:

a) The positive aspects of CTS/Hermes operations are not included.

b) The design, integration, test, launch, spin and attitude acquisition phases of operations are not included.

c) CTS/Hermes was a geostationary satellite, and hence always within view of the ground-station.

d) The satellite was three-axis stabilized; in addition to the obvious ACS/RCS requirements, this implies a totally different thermal/power environment from spinners.

e) The whole program was experimental, so the behaviour of the satellite was less predictable than that of an operational spacecraft, and its control was heavily dependent on telemetered data.

While some of the recommendations appear obvious, significant problems arose in CTS/Hermes on-orbit operations because they were overlooked or underemphasized.
It is hoped that their inclusion here will help avoid or reduce similar problems on future spacecraft.

Note that more detailed comments/recommendations based on several of the problems with greatest impact are given in the reports of various review boards (References 5-10).

## 3.2 General Recommendations

The recommendations in this section are those that apply to the whole project; many of the points included at the subsystem level (in Section 3.3 of this report) are particular cases of general areas covered here.

3.2.1 The design of the spacecraft and the ground control centre should proceed from an overall specification of the total system requirements and constraints.
In turn, design of S/C subsystems should proceed from an overall S/C system specification, and design of G/S subsystems (hardware, software, operating procedures, etc.) should proceed from an overall G/S system specification.

3.2.2 Throughout all phases of design, manufacture/procurement, integration and test, effective system-level control must be exercised, with particular attention paid to interfacing between the S/C and G/S, and between subsystems in each.

3.2.3 Configuration documentation and control must be detailed, complete , and constantly updated throughout both pre-launch and post-launch phases.

3.2.4 Failure modes and effects analysis (FMEA) must begin early in the design phase, and must be continuously updated throughout both pre-launch and post-launch phases.

3.2.5 Real-time mission simulation, using both computer models and H/W models of the S/C, should be used to test and evaluate H/W, S/W and operational methods and techniques, and to train operations personnel, starting with the Engineering Model, and continuing throughout life.

3.2.6 Any elements of the system that are shown to be inadequate by FMEA, simulation or test must be modified or replaced as appropriate, and resources must be available to permit this. Testing of replacements and of modified items must be rigorous and complete. Modification (e.g. refurbishment of H/W) is not acceptable unless the causes of the problem are completely understood and corrected.

3.2.7 Throughout pre-launch phase, a strong emphasis must be placed on reliability and facility of on-orbit operations. Decisions and trade-offs based solely on weight, cost and schedule constraints can have severe operational consequences up to and including jeopardizing the mission.

3.2.8 Detailed study of redundancy requirements is essential; in particular, where possible:

i) Partial redundancy must be avoided.

ii) Redundant units should be generically different.

3.2.9 In the conceptual design phase, a system level trade-off is required between automatic on-board operation, automatic ground control, and manual ground control of all aspects of S/C operations. It must include:

i) Dependence on, and reliability of, all elements of the uplink/downlink loop (ground H/W and S/W, space H/W, RF signals, personnel, etc.).

ii) Penalties implied in the use of on-board H/W, particularly in cost and schedule due to qualification and test requirements.

iii) The inherent flexibility of ground S/W and H/W vs possible use of programmable microprocessors to provide on-board flexibility.

Note that geostationary satellites are always within view of the G/S, so the high degree of autonomous on-board control required for non-stationary satellites is perhaps not necessary.

3.2.10 Allocation of resources (particularly manpower) must allow for:

i) Turn-over in personnel, and the training of replacements, throughout pre-launch and post-launch operations.

ii) The occurrence of unforeseen anomalies, failures, etc. post-launch, requiring analysis, development and testing of work-arounds, etc. (particularly on an experimental satellite).

iii) The modification of on-orbit operations to meet new goals (e.g. extended life, greater accuracy in orbit control, etc.), requiring design, development, testing, and implementation of procedures, and analysis of consequences.

## 3.3 Subsystem Recommendations

### 3.3.1 SHF Transponder and Beacon

a) Uplink power and frequency must be maintained within limits. This is difficult when there are many different sources of uplink signals.

b) Cathodes should remain at least partially heated at all times; care must be taken to avoid stripping when high voltage is off.

c) Command sequencing/timing constraints must be built into ground S/W. Note that:

i) These constraints must be supplied to the S/W designers as early as possible.

ii) Building such constraints in the on-board hardware is not advisable due to inflexibility.

d) Testing should include some measurement of expected behaviour in normal operations (as well as at extremes). This data should be available to the operations group before launch, and specialist support should be maintained after launch to confirm and, if necessary, modify the predictions to cover the remainder of life.

e) Outgassing in high voltage components (particularly when the power level changes significantly) can be a problem, and should be eliminated if possible. Tests must check on the potential for arcing due to outgassing, and components (e.g. connectors) redesigned if necessary.

f) Trip circuits are extremely useful, but must be protected against EMI (particularly from arcing - see e); sensitivity must be carefully controlled to maintain protection while eliminating unnecessary trips.

g) When testing shows a sensor is unreliable (e.g. thermally unstable), and it is not corrected before launch, the information must be supplied to the operations group. If possible, ground S/W should be modified to correct the data, or perhaps modify its display so it will not incorrectly impact operations.

h) Thermal effects on transmitted signals (strengths and frequencies ) are significant; components must be designed and tested to minimize them. Predicted magnitudes, etc. should be provided to the operations group.

### 3.3.2 SHF Antennas

a) Incorporate an on-board switch to turn off the drive motors before hitting antenna stops.

b) Ground S/W command structure must include a simplified antenna slew system using a standard step size, slew rate, etc., with checks to avoid over-slewing.

c) Telemetered antenna positions should have the same resolution as the commandable step-size.

d) Detailed analysis is required (pre-launch) of the causes, effects, significance, measurement and correction of deviations from nominal of antenna pointing. Periodic measurements are required throughout life.

### 3.3.3 Telemetry, Tracking and Command

a) In the conceptual design phase, a system-level study is required of dependence on, and reliability of, telemetry. Increasing on-board automatic control (e.g. ACS control loops, thermostatically controlled heaters, etc.) reduces the impact of failures in the S/C telemetry system and on the ground; increasing ground control (S/W or operator initiated heater control, etc.) reduces the amount of space-qualified hardware required, and allows much greater operational flexibility (particularly significant on an experimental satellite).

b) For all critical components (e.g. telemetry transmitters), redundancy is essential, but a system-level study is required to determine whether redundant units should be generically identical or not. If no identical units have previously been successfully operated in space, the backup should be generically different from the prime. If this is precluded (e.g. by cost), extremely rigorous and complete ground testing is essential.

c) Ground tests must include many thermal cycles, with continuity testing of all critical components (e.g. transmitters) during temperature transitions.

d) Provide the capability for transmission of telemetry, and for ranging, via other communications channels (i.e. SHF).

e) A system-level study of the integrity of the command loop is required, particularly to cover anomalous situations (attitude, telemetry, etc.).

f) A system-level study of the telemetry structure is required, including:

i) Is each piece of data useful and/or necessary.

ii) What word-length and repetition frequency is required for each piece of data.

iii) What overall bit-rate and frame-length is required.

iv) How should the resulting structure be implemented (digital vs analog words, processing in Encoder or at S/S level, sub-commutation, super-commutation, etc.).

g) Do not use non-redundant telemetry Encoders; despite possible weight, cost and reliability penalties, sub-commutation of data is a much better way of reducing the number of channels required.

h) A system-level study is required of causes and effects of variations in clock frequencies; such variations must be minimized (in particular, avoid changing sources), and test data on expected behaviour must be available to operations planners and ground S/W designers at an early stage.

i) Provide commandable $4\pi$ steradian telemetry coverage; should be used only for attitude acquisition and reacquisition to avoid interfering with other satellites. Perhaps automated if $4\pi$ steradian earth sensors used.

j) Transmitter and receiver must be designed to minimize variations in frequency; the whole uplink/downlink system should operate so that loss of lock does not cause significant changes in the frequency of any of the components.

k) A system-level study of command structure is required, including manipulation in ground S/W vs S/C H/W, inclusion of timing capability, effects of multi-function commands (particularly in non-standard situations), etc. Some goals should be:

   i) Procedures and operator inputs must be simple and clear.

   ii) Unnecessary cycling of on-board equipment should be eliminated.

   iii) Meaningful checks on safety and appropriateness of commands should be included; potentially harmful command sequences should be avoided.

   iv) All potentially desirable S/C states must be directly commandable.

   The emphasis should be on operability, particularly over the long term, and non-standard situations must be included.

l) Multiple function commands should be eliminated; value commands can be used to avoid exceeding command channel capability, and ground S/W modified to keep inputs simple (e.g. by grouping commands), while maintaining flexibility.

m) It should be recognized that a high-accuracy ranging system is an important tool in analyzing RCS performance; this may be a more stringent requirement than orbit determination.

3.3.4 Power

a) It is possible that NiCd batteries are not adequate for long-life operational satellites. Perhaps, for example, metal hydride batteries are required.

b) Do not integrate flight batteries on S/C until the last possible moment; locate batteries on S/C for easy access/removal/replacement. Avoid subjecting flight batteries to harsh pre-launch environment (test and storage); use engineering model batteries (or other spares) for S/C level testing wherever possible.

c) Use heat pipes and thermostatically controlled heaters and louvres to:

   i) Maintain batteries between 0°C and 15°C.

   ii) Minimize temperature differences between batteries, and between cells of each battery.

d) Battery thermal environment is critically important and must be very thoroughly analyzed and tested before launch. Modelling must include as much detail as possible (a single node approach is not adequate), and any structural changes from those modelled must be avoided, or the analysis repeated with the new configuration.

e) Battery charging capability must include a high rate (~C/3) charge and either a voltage controlled, temperature compensated taper charge (with commandable voltage level), or a "trickle" charge (essentially to maintain a bias on the batteries when not in use).

f) A battery reconditioning system is mandatory and must include a high rate discharge (~C/3), and a low rate discharge (~C/50) for use below 1 volt/cell. The system (including telemetry data) must be capable of discharge to at least 0.6 volts/cell, and the discharge resistors must be qualified for use at all orbit slots.

g) If weight, cost and reliability permit, cell-by-bell shorting and telemetry would permit a major improvement in battery operations/behaviour.

h) Batteries should be made as independent of each other as possible; if S/C safety requires parallel operations, an adjustable isolating impedance must be provided.

i) Charge controllers must be designed to handle simultaneous high rate charging of all batteries, at high bus voltages.

j) Battery current sensors must provide high accuracies at low currents, as well as covering the full range of currents possible. The data must be available at all times (i.e. do not use non-redundant Encoders), and care is necessary to avoid discharge currents biasing charge current sensors, and vice-versa.

k) Pre-launch test/analysis/simulation/etc. must provide accurate information on:

   i) Usable battery capacity, and its expected behaviour over life.

   ii) How to determine when a battery is fully charged.

   iii) How to measure/estimate the usable capacity of a battery on-orbit.

l) It should be recognized that battery management is a very complex, time-consuming task. Consideration should be given to including on-board programmable microprocessors; if this is not feasible, sophisticated automatic ground S/W should be implemented, and operators trained in its use.

m) Under-voltage protection of the batteries is necessary, but a system-level study is required pre-launch, including:

   i) What components should be switched off by under-voltage sensor (UVS) trip; it seems preferable to at least maintain telemetry.

   ii) Under what circumstance should UVS trip, and when will undesirable trips occur.

   iii) How to recover from UVS trips.

   The UVS system must be completely over-rideable, and must have commandable voltage levels (different for each battery). Flexibility in what components are switched off would be an advantage. UVS Enable/Disable must not be made part of any other command.

n) Detailed analysis/testing of thermal/power transients on light-weight, extensive solar arrays is difficult but essential (particularly eclipse entry and exit). Under-voltage and overvoltage protection is necessary, but should be kept simple, while still capable of handling extremely rapid, large scale voltage transients (on a cold, unloaded array). Ground over-ride of the OVC/UVC must exist, along with telemetered data on array voltages (as distinct from bus voltages).

o) A detailed and complete failure modes and effects analysis is essential for all high power circuits. Particular attention should be paid to potential sneak paths, and to multi-redundant relay systems. Perhaps series-redundant relays should not be used in high power circuits.

p) Complete data on power converter behaviour (particularly losses) must be obtained in testing, and incorporated in ground S/W. Effects of temperature, etc. must be included. Data must extend well beyond normal operating ranges to cover non-standard situations.

q) A simple and direct method of measuring array power capability on-orbit must be included.

r) Arrays must be sized to take into account (predictable) solar cell degradation, plus some margin for anomalies.

s) Body array system should be desiged so that:

   i) It is not necessary to jettison H/W when the main arrays are deployed.

   ii) The body arrays do not have negative impact on on-orbit operations (e.g. unloaded cold body arrays holding H/K array OVC open post-eclipse).

   iii) Power from the body arrays is usable on-orbit (particularly in non-standard attitudes).

t) Whenever possible, power-on resets should be applied to all components downstream of a power supply before power is supplied to them.

u) Do not use logic switches where power controlling the switch can be off at the same time as power through the switch is on. Either use latching relays, or use a common power supply.

v) Where a specific sequence is required in powering up components, it should be automated (in ground S/W rather than on-board, to maintain flexibility).

w) Power/thermal design must take into account the possibility of long (up to 3 hours) eclipses of the sun by the moon.

x) Accurate and complete calibration data must be provided to the operations group well before launch. Ground S/W calibration system must be flexible enough to include a variety of functional forms, and the effects of one parameter on others.

3.3.5 Spacecraft Harness and Electrical Integration Assembly

a) Good EMI protection and testing is essential (see 3.3.11).

b) Perhaps the EIA should be used to sub-commutate temperature data (see 3.3.3) and/or to provide independent control of each heater (see 3.3.10).

3.3.6 Attitude Control

a) i) The earth sensor system must be designed so that complete redundancy exists; if this is not feasible, design, manufacture and test must be drastically upgraded, a complete and rigorous FMEA must be applied, and detailed recognition/recovery/work-around procedures developed and tested before launch to cover any failures.

ii) Earth sensors should be designed to minimize the effects of interferences (e.g. include radiance limiters to cut out the sun), and to eliminate ambiguous outputs.

iii) Detailed predictions of sun and moon interferences with earth sensors (including number, frequency and intensity) must be available early in design phase; preliminary operations planning using this data may indicate the need for changes in the sensor or ACS design.

b) Extremely rigorous testing of earth sensors, particularly for the effects of thermal gradients, and thermal and power cycling, is essential. If possible, earth sensors should not contain any moving parts.

c) i) Do not fly critical components that fail during pre-launch testing; flight qualified spares should be available. Resources must be made available to ensure that the causes of any failure are completely understood, and that the replacement (and any other similar units) will not fail in the same way.

ii) If refurbishment of a failed unit is forced (because cost constraints preclude carrying enough flight spares, of because all flight qualified units fail), resources must be available to ensure that:

- the causes of the failure are completely understood and corrected, and
- all refurbished units are tested rigorously and completely.

d) Automatic Failure Protection against attitude anomalies is essential, but:

   i) All thrusting must be totalling inhibited.

   ii) Resulting S/C rates must be minimized (requires high accuracy, high speed on-board wheel speed measurement).

   iii) Ground commandable selection of parameters that can trigger AFP should be included.

e) A secondary attitude sensing system should be provided; if the prime sensor indicates a problem, the secondary system should be checked, and its outputs used for attitude control (possibly degraded), if it indicates the anomaly is in the prime sensor rather than in S/C attitude. It may be necessary to use several sensors with a "voting" system. Detailed system-level design (including a rigorous FMEA) is required before implementing such a system.

f) Automatic attitude reacquisition capability should exist. The trade-off between on-board and on-ground implementation is very complex, but given that an on-board system would require ground backup (in case it failed), and that flexibility is essential, perhaps ground S/W is the better approach (assuming reasonable telemetry). Note that such a system must not use any components that may have caused the anomaly (e.g. prime earth sensors) until after ground analysis proves they are operating correctly.

g) The choice of which sensor outputs are used by the automatic attitude control loops must be made by ground commandable logic switching, not by power switching.

h) Attitude control loops must include passive, benign, long-term stable modes; systems with one biased momentum wheel provide this capability in two axes, and the third can be implemented by using a backup rate integrating gyro, applying an averaged duty cycle to the wheel, etc. Systems with two non-aligned biased momentum wheels can provide this capability in all three axes..

i) Extensive testing of momentum wheels is essential; particular attention must be paid to detecting cage instability, and the wheel must be rejected if it appears (refurbishment is not acceptable). The effects of thermal gradients and cycling on the bearings and lubricant are also important.

j) Control loop design must allow for wide variations in critical parameters, including damping in flexible appendages, sensor time delays, mass properties, misalignments, wheel drag torques, thruster impluse-bits, etc. To achieve sufficient flexibility it is probably necessary to use on-board programmable microprocessors, particularly for long-life satellites. If this is not done, a minimum requirement is for sufficient resources to allow modification of the attitude control electronics after all flight hardware characteristics have been measured as accurately and completely as possible. Note that microprocessors may introduce problems of their own.

k) Design and simulation of ACS must included complete and accurate modelling of array operations (standard sun-track, standard fast-slew, and various non-standard operations, including slewing of a single array). The detailed form of the torques applied to the array is important; some form of essentially constant torque drive is preferrable from an ACS point of view.
The coupling of array pitch motion into S/C roll-yaw is significant (even for rigid arrays) and must be included in analysis and simulation.

l) Large-scale thruster activity can cause large-scale perturbations in attitude, wheel speed, etc. To minimize this:

i) Pre-launch design and integration must minimize thruster misalignments and centre of mass variations (e.g. perhaps a split array is preferable).

ii) Design operations so thruster activity occurs in small, frequently repeated blocks, rather than a few very large operations. The large manpower requirements implied by this can be reduced by automating E-W S/K, N-S S/K and M/D, preferably in ground S/W.

iii) Periodically throughout life, calibration measurements are required of thruster misalignments, mass properties, plume impingement effects, thruster mismatch, etc. Operations, schedules, etc. should be modified to compensate for these effects.

iv) If possible, avoid the use of pairs of thrusters, where mismatch would cause large attitude disturbances. If this is not possible (e.g. for N-S S/K), adequate sensing (e.g. a good yaw sensor) and control (preferably using ground S/W for flexibility) must be provided.

m) i) $4\pi$ steradian sun sensing is essential, and must be available at all times; careful design is required to handle head cross-overs and to avoid glinting problems.

ii) Relatively coarse $4\pi$ steradian earth sensing (or its equivalent in e.g. rate integrating gyros) should be available for use in non-standard situations.

iii) Third axis (yaw) angle and rate information should be readily available; this can be obtained from either high sensitivity sun sensors (~0.25° resolution), a star tracker, a high accuracy rate integrating gyro, or a state estimation system (which would integrate sensor outputs, mass properties data, dynamics, etc. to provide the information indirectly). The state estimation approach appears to be better (in cost, etc.); it should be implemented in ground S/W (for flexibility), and can be extended to provide estimates of angles and rates when data is unavailable or degraded (due to sensor or telemetry problems, sun-earth-S/C alignment, etc.).

n) Bias capability must exist for all sensor outputs used in automatic on-board control. Independent biases are required for each sensor output (<u>not</u> for each control input), and they must be separately and easily commandable. Biases can be very useful in optimizing attitude control, but considerable resources are required for analysis and implementation.

o) i) When using a single, biased momentum wheel, the control system (in roll-yaw) must be optimized to properly damp the nutation cone (thus avoiding double dead-banding and minimizing the required number of pulses). See 3.3.6 j re flexibility requirements.

ii) The wheel speed operating range should be at least three times the predicted requirements to cover anomalies, unplanned operations, etc. Shaping and smoothing of the torque-speed curve should be done in the control electronics (rather than the driver/motor hardware), perhaps using programmable on-board microprocessors.

iii) The tachometer must measure wheel speed to better than 0.1% of the nominal operating range. It should be recognized that wheel speed is a critical parameter in operations planning and design, and in ACS/RCS performance analysis and prediction.

iv) Ground S/W must provide proper averaging of wheel speed, and correction of such effects as S/C clock variations.

p) i) Independent pulse count and duration telemetry for each thruster is essential (for performance analysis, detecting problems, etc.); registers should be sized to cover both a full day of normal operations and the maximum possible activity in non-standard situations.

ii) Zeroing registers after sampling must be avoided.

iii) Ground S/W should include correlation of this data to provide time and duration of each pulse, with automatic recording of the results.

q) Prediction of expected ACS behaviour, and daily monitoring of all critical parameters, is essential (particularly on experimental satellites) to provide warning of problems, and a data base for predicting future performance. Leaking and anomalous firing of thrusters is especially significant and hard to detect.

r) Pre-launch analysis and post-launch calibration of the effects of all thruster firings on the orbit is required; off-line orbit determination/prediction S/W should include such effects, particularly regular daily impulse (e.g. from the offset thrusters).

s) Alignment of all attitude sensors is critical; particular attention must be paid to pre-launch prediction and post-launch calibration of variations in alignment, and how to correct for their effects (using biases, etc.).

t) If heat pipes and louvres are used (see 3.3.10), ACS design must take into account torques generated by:

i) fluid transfer in heat pipes;

ii) solar pressure on open louvres;

iii) changing the orientation of louvres.

### 3.3.7 Structures and Mechanisms

a) i) Mass properties have a major impact on operations, and are critically important in ACS/RCS performance analysis and prediction. Pre-launch analysis and measurement must provide accurate estimates of all mass properties including the expected variations (daily, yearly, and over life), and the maximum dispersions in the data. Tight control, and good documentation are essential.

ii) The impact of the predicted mass properties on operations and performance must be thoroughly analysed early enough to allow H/W changes (e.g. to ACS control loops) if necessary. Non-standard situations should be included.

iii) On-orbit variations in mass properties must be minimized (e.g. perhaps a split array is preferable).

iv) A systematic measurement of on-orbit mass properties should be implemented.

v) Data on predicted and measured mass properties must be readily available to operations personnel both before and after launch.

b) i) The accurate alignment of many components (including attitude sensors, thrusters, wheel, antennas, etc.) is extremely important. The combination of initial misalignment, and changes due to space environment (zero-g, thermal extremes, etc.) must be carefully analyzed for impact on operations and performance in standard and non-standard situations.

ii) Systematic measurement of misalignments on-orbit should be implemented, and methods of correction (ACS biases, vectorable thrusters, antenna pointing adjustments, etc.) included in H/W, S/W and operations design.

c) Structural damping, particularly in the flexible arrays, is very difficult to estimate, and has a major impact on ACS design. Analysis/measurement methods should be developed to provide realistic numbers.

d) Array orientation control should be kept as simple as possible (consistent with reliability requirements). An automatic, on-board, sun-tracking controller should be implemented incorporating:

i) Sun sensors with fields of view of at least $2\pi$ steradians; high accuracy (~0.5°) is necessary only within normal operating ranges.

ii) An essentially continuous torque drive system, capable of rates up to the maximum expected S/C rate following AFP trip (see 3.3.6 d).

iii) A level of sophistication sufficient to maintain sun-tracking without wasting power in most non-standard situations.

iv) Ground commandable modifications to controller parameters.

v) Power-on reset for all logic states.

On-board programmable microprocessors may be necessary. Full-scale life-testing of the controller/driver and a complete FMEA are essential.

e) Array orientation telemetry must include:

i) Unambiguous indication of the array position relative to the sun and to the S/C body.

ii) Unambiguous flagging of controller/driver modes.

f) If possible, design of body arrays/deployable arrays should not require jettison of hardware.

### 3.3.8 Reaction Control

a) Low thrust hydrazine systems exhibit large-scale variable degradation in performance, with major negative impacts on operations. These problems must be taken into account when selecting the thrust/torque system during design phase. Other potential candidates include ion engines, magnetic torquers, bi-propellant systems, cold gas systems, etc.

b) If a hydrazine system is used:

i) Detailed analysis/testing is required to determine whether additional thruster activity due to under-performance consumes additional fuel. It is probably necessary to carry extra fuel (perhaps twice nominal) to compensate.

ii) Attitude control systems (on-board and in ground S/W) must allow for significant, variable, unpredictable degradation in thrust level.

iii) H/W, S/W and procedures must be designed to eliminate uncontrolled thruster firing with latch valves closed, as gas in the lines will cause significant impulse to be delivered.

iv) Use of pairs of thrusters where mis-match will cause attitude problems should be avoided. Where this is unavoidable (appears likely for N-S S/K), control systems must be capable of handling large-scale mis-match (possibly up to 100%).

v) Multiple back-up thrusters must be carried.

c) The performance of the roll-yaw offset thrusters is critical to mission success, but very difficult to measure due to complex control systems, etc. Detailed methods for measuring and predicting performance must be developed pre-launch, and properly implemented on-orbit.

d) Detailed analysis of the rate of auto-decomposition of hydrazine at various temperatures is required pre-launch. Temperature ranges which reduce the rate to an acceptable level must be selected, and the thermal control system and operations designed to meet these requirements. Temperature telemetry must be adequate to check that the requirements are met on-orbit, and operations/hardware must permit modifications if necessary.

e) If a pressurized, blow-down fuel supply system is used:

i) Diaphragm material must be carefully selected and tested to minimize permeation of pressurant into the fuel, and to avoid degradation/break-up.

ii) Design and test must cover the operation of all valves under conditions of maximum pressure differential.

iii) Pressure transducers must be protected against pressure spikes due to opening or closing valves.

iv) High accuracy telemetry is required for pressurant temperature and pressure if they are to be used to determine the amount of fuel remaining. The temperature sensor must be properly thermally coupled to the pressurant.

v) Some means (other than the blow-down curve or performance prediction) should be available to calculate remaining fuel in each tank. Possibly a system for detecting diaphragm position/shape is feasible.

vi) Pre-launch analysis of the mass properties of the fuel system is required, with emphasis on changes due to fuel use, temperature variations, fuel transfer between tanks, etc.

vii) Perhaps a four-tank (rather than a two-tank) fuel system should be used.

f) RCS thermal control must be integrated with overall S/C thermal control, and should be designed such at:

   i) Temperature extremes (hot and cold) are minimized.

   ii) Telemetry includes the temperatures of all critical components; specifically, all thrust chamber temperatures must be available.

   iii) Heaters are broken up into small, separately commandable elements (to avoid the situations where heating a cold area requires overheating a warm area, and where several thrusters are heated when only one is required).

   iv) Operations are as simple and reliable as possible.

   v) Heater failures are easily identifiable, and redundant heaters are available.

g) Thruster valve materials and design must be selected and tested to minimize degradation and distortion, particularly due to temperature extremes.

h) Catalyst bed materials and design must be such that no poisoning, washout, break-up, or other deterioration will occur.

i) Thusters must be designed to fire cold when necessary (to avoid time delays and reduce power usage in anomalous situations).

j) Detailed analysis and test of heat soakback from thruster firings is required.
Many intermediate values of temperature and pressure must be included to cover the possibility of flashback.

k) Backup thrusters and heaters must be designed to have essentially the same impact (thermal and power, as well as thrust and torque) as the prime thrusters.

l) See 3.3.6 c

m) Pre-launch performance prediction data should cover a considerably wider range than planned operations (to allow for non-standard situations and operations introduced after launch).

### 3.3.9 Apogee Motor

a) Accurate conductance modelling of the expended apogee motor is essential.

b) Accurate prediction (pre-launch) and measurement (on-orbit) of the mass properties of the expended apogee motor is necessary.

### 3.3.10 Thermal

a) Overall design, simulation and testing must include recognition of:

i) Large E-W and N-S thermal gradients, and large daily and yearly temperature variations experienced by three-axis stabilized satellites (as opposed to spinners).

ii) The variability of S/C operational modes, and the large thermal impact this can have, particularly on high-powered satellites.

b) As a result of a), active thermal control elements are essential. In general:

i) Heat pipes should be used to distribute heat inside the S/C. In particular they should be used to minimize temperature differences between batteries and between cells on each battery. Heat pipes should not be exposed directly to space; if this proves necessary, detailed analysis/testing is required to ensure that the fluid will not freeze.

ii) Louvres should be used to control the heat radiated to space from the whole S/C (particularly during eclipses and in non-standard situations), and from specific areas (e.g. batteries).
Thermostatic control improves reliability (particularly in non-standard situations) and reduces the complexity of ground operations.

iii) Thermostatically controlled heaters should be used to maintain the temperature of components exposed directly to space, and to replace heat lost when component dissipations change (e.g. at turn-off).

c) All aspects of thermal environment and control must be integrated right from the start of design.
Specifically, RCS thermal control must be integrated with the rest of the thermal S/S.

d) Thermal design should be directed towards simple, reliable operational procedures, S/W, etc.
Some implications are:

i) Thermostatic control of heaters and louvres is necessary, but temperature limits must be flexible, and ground over-ride capability must exist. Perhaps programmable on-board microprocessors should be used.

ii) Heaters must be broken up into small, separately controlled elements positioned such that areas that experience significantly different thermal environments do not share the same heater.

iii) The number of heater cycles required, and the number and extent of louvre movements, must be carefully analyzed, and the impacts on reliability taken into account.

e) Temperature sensors must be positioned and thermally coupled to the S/C to provide:

i) Adequate heater control (on-board and through ground command).

ii) Sufficient information to determine whether each heater is operating correctly.

iii) Enough data to adequately determine the thermal status of the overall S/C, and of components subject to thermal extremes or sensitive to thermal variations (particularly solar arrays).

f) All necessary temperature data and heater flags must be available at all times (i.e. do not use non-redundant TM Encoders). Note, however, that high rate temperature TM is not required and thus sub-commutation can be used.

g) Detailed predictions of expected thermal behaviour (including heater operations, other S/C operations, effects of degradations, etc.) must be available to the operations group before launch, and should be updated throughout life using real S/C data. (Good off-line data processing is a necessity).
The predictions require analysis, testing and simulation between and beyond, as well as at, specification limits, and should include non-standard situations (heater/louvre failure, loss of S/C power, operational errors, etc.).

h) Pre-launch testing must include:

i) A wide range of temperature beyond expected; ±30°C may be required on some components to cover inaccuracies in modelling and assumptions, changes in operations, etc.

ii) Continuity testing of all components during temperature transitions (particularly in S/C level tests).

iii) At least five or six thermal-vacuum cycles on the complete S/C.

iv) The effects of one part of the S/C shadowing another part.

v) Detailed checks on distribution of heat generated in all high power elements, particularly relays.

vi) Extensive thermal cycling of critical components, with checks on operability at points throughout the cycles.

i) Specialist support must be maintained throughout life to analyze S/C data and provide:

i) updates to predictions (see 3.3.10 g), and reasons for deviations from the predictions;

ii) warnings of potential problems;

iii) modifications to operational procedures, S/W, etc. to cover changes in operational modes, problems, failures, etc.

j) Thermal transients at eclipse entry and exit, especially on light-weight, low thermal mass, extensive solar arrays, have a major impact (particularly on the power S/S - see 3.3.4). Detailed analysis, simulation and test is difficult but essential.

k) Thermal design must include the possibility of long (up to three hours) eclipses of the sun by the moon.

l) Detailed pre-launch analysis and post-launch calibration of thermal effects on mass properties and alignments is required (see 3.3.7).

m) The batteries are extremely sensitive to thermal environment. In addition to using heat pipes to reduce temperature spreads (see 3.3.10 b):

   i) High accuracy simulation/modelling is essential (a single node approach is not adequate).

   ii) Cell-by-cell temperature telemetry should be available.

   iii) Battery temperatures should be maintained between 0°C and 15°C under all charge/discharge situations, using heaters and louvres.

   iv) Minor structural changes can have significant thermal impact, and such effects must be analyzed in detail.

n) Battery reconditioning resistors must be thermally qualified to be usable at any orbit slot.

o) Battery charge controllers must be thermally designed to handle all required charge current/voltage combinations.

p) Resources must be available to replace components that fail, or show marginal operation, in thermal test.

q) Detailed analysis and test is required of the thermal interaction between the RCS and the rest of the S/C - see 3.3.8 for detailed recommendations.

r) Good thermal modelling is essential; some areas requiring special attention include:

   i) Extendible solar arrays;

   ii) Batteries;

   iii) RCS thrusters;

   iv) Expended apogee motor conductance;

   v) Multiple solar reflections between angled surfaces.

3.3.11 <u>SATE, TEC, S/C Charging, etc.</u>

a) Deployable solar arrays must be designed with backside shielding approximately equivalent to the front. Possible methods include:

   i) Use of a conductive grounded layer on the back side.

   ii) Use of a thin aluminum honeycomb substrate.

b) Command and data line circuits (including trip circuits) must provide protection against short, high-level transients.

c) All second surface mirrors must be bonded with conductive adhesives.

d) All layers of thermal blankets, and all metal parts, must be properly grounded.

e) S/C level EMI testing using a very fast spark source is essential. Results of engienering model tests should be used to specify EMI protection of flight components.

f) Emission and susceptibility levels of telemetry and command lines should be tightly limited by EMI specifications.

g) A system for detecting and analyzing electromagnetic transients should be implemented, including:

   i) an external electromagnetic environment monitor on-board;

   ii) independent sensors and counters on all critical lines;

   iii) isolation of on-board power supplies from the transient sensors;

   iv) adequate off-line ground data processing and analysis, with emphasis on correlating transients with other S/C events, particularly anomalies.

h) Instrumentation of flexible solar arrays is essential and should include deflection sensors, accelerometers, tension monitors, extension monitors, temperature sensors, and methods for measuring array power capabilities and solar cell degradation.

### 3.3.12 Transmitter Experiment Package

a) All of the recommendations of 3.3.1 apply to this subsystem as well.

b) Heat pipes are a good method of removing heat from high power tubes and power processors. The system used to radiate this heat from the S/C must be carefully protected against freezing, perhaps by closing off louvres over the radiating surface when it is not in use.

c) Protection against, and testing for, the effects of high power, high frequency radiation on the S/C (particularly IR sensors, and telemetry and command lines) is essential.

d) Transmissions that are essentially independent of uplink are extremely useful and should be incorporated if possible. At least one such signal per communications antenna (steerable or fixed) should be included (along with an independent beacon), and they should be battery powered (for access in emergencies).

e) Good TM data on S/C power levels (uplink and downlink) is essential; ground S/W must provide the capability of properly calibrating such data, and of modifying it for the effects of temperatures, etc.

f) High power systems must be designed to minimize surge currents (e.g. at relay closing), and the effects of such transients must be carefully analyzed and tested.

### 3.3.13 Ground Station Non-Computing Hardware

a) Ground antenna updating (S-band and SHF) should use auto-track while a downlink is available, with a programmable microprocessor to control pointing (using high accuracy orbit predictions) otherwise.

b) The complete S-band loop (ground transmitter, S/C receiver, S/C transmitter, ground receiver) should be designed to minimize frequency variations; in particular, step changes in S/C Rx and Tx frequencies due to loss of uplink lock, and in ground Rx frequency due to loss of downlink lock, should be eliminated if possible.

c) Automatic frequency sweep systems should be readily available on all ground receivers, and on the S-band transmitter. Careful matching to ground and S/C Tx and Rx characteristics is essential, and the systems should be designed to maximize the probability of achieving lock while minimizing the time required.

d) Ground equipment (particularly the S-band system) must be fully protected against EMI and power failures. Perhaps a battery and/or capacitive storage system should be used.

e) The critical importance of ground systems in the successful operation of a satellite must be recognized early in the program, and hardware, software, testing, calibration, etc. designed accordingly.
Interfacing (between different components in the G/S, between G/S and S/C, and between operations personnel and G/S H/W) is particularly complex and significant. On-orbit, periodic test and calibration of all ground H/W is required, and adequate spare parts must be carried for all essential components.

f) Ground received signal strengths are important parameters in S/C operations and analysis, and measurement and recording of such data is essential. Analysis of, and allowance for, the effects of weather, ionosphere, etc. is necessary. Losses and variations due to ground equipment should be minimized by:

   i) accurate antenna pointing (see 3.3.13 a);

   ii) dehydration of waveguides (using dry air compressors and automatic regenerators);

   iii) de-icing of antennas (perhaps using low-level heating currents);

   iv) protecting against EMI (see 3.3.13 d);

   and various other means.

g) Checks on operability and mode should be built into all critical ground equipment, with feed-back to the control computer for display, warnings, and (if possible) correction. This is particularly important for all elements of the command link.

h) Strip chart recorders are extremely important for data recording and on-line analysis. Regular, systematic testing, maintenance, and scaling and calibration are required. The charts must be annotated in detail with pen assignments, scales, chart speeds and times; if feasible, an automatic printing system should be used to provide this. It would also be advantageous if control and monitoring of SCR status from the computer were available.

i) Detailed, accurate, complete, up to date, readily accessible documentation is essential, and must include:

   i) The H/W patching/switching system (standard modes, procedures for changes, etc.).

   ii) Command logs that incorporate all commands sent to the S/C, together with individual command descriptors and brief descriptions of operations, discrepancies and anomalies. If feasible, this should be automated in the off-line data processing system.

   iii) Operations schedules that are available for review before implementation.

   iv) Descriptions of all H/W, along with test, maintenance and calibration procedures.

   v) H/W status reports.

j) High quality analogue recording of the S-band downlink is essential (to provide data covering computer down-times, etc.), and requires good record/playback H/W.

### 3.3.14 Ground Station Computing Hardware

The major computational problem on CTS/Hermes was the general inadequacy of the HP2100 and HP-MX to their assigned on-line, real-time tasks. The Systems Group was originally told to use one HP2100 for all Attitude Acquisition and On-Orbit tasks before any analysis was done as the the extent of the eventual requirements. The fact that the HP's were too small from a core storage point-of-view and generally too slow from a standard real-time operating system response viewpoint, compromised several on-orbit operations and unnecessarily complicated the ground station computing system development and checkout.

As the eventual computing requirement was too large for core and the real-time data update requirement of once per second was very time critical, a large and costly Operating System (OS) development program was undertaken too soon before launch. The small Systems Group was required to spend the majority of its time on computer development and checkout, instead of concentrating on spacecraft Detailed Operating Procedures (DOP) or on-orbit applications programming. The net result was that the ground station computing system was not completely debugged by the start of the On-Orbit Mission Phase nor were the DOP's complete or rigorous. Also during the entire On-Orbit phase, the computing system was incapable of easy extension, major modification or growth.

It is recommended that a reasonable estimate of the total on-line computing requirement be made before a trade-off study is performed to determine the most suitable computing hardware/software. A non-standard Operating System executive development program should not be required if the appropriate, capable system is first selected. The major development and implementation of the Ground Station computing system (excluding normal applications programming) should be completed by the S/C test phase of the program. The system so designed or selected, should be capable of straight forward expansion or modification based on actual flight or test experience.

### 3.3.15 Ground Station Software

The criticisms of 3.3.14 apply equally well here. Because of the general inadequacy of the hardware, various software programs were incomplete or inadequate. See Section 15 of the Appendix for specific examples.

The recommendations of 3.3.14 also apply here. All system level software development should be finalized along with total Ground Station implementation by the S/C test phase of the program. Application's programming would be a continuous process extending through S/C test, launch, and on-orbit operations. It would of course be bound by normal codes of debug/implementation and configuration control.

3.3.16 NASA/STDN Hardware/Software

Include any NASA/Ground Station data/command interface requirements in early Mission Planning and assess the implications on ground station hardware/software.

3.3.17 Systems Planning, Test and Analysis

a) At the inception of any future spacecraft project, there is the requirement for early and experienced overall system direction and planning. The system's group (space segment and ground segment) should have sufficient manpower and computer simulation resources to engage in long range planning as well as day-to-day problem solving activity. It is very tempting to forego on-orbit planning for more immediate test and attitude acquisition planning, as was done on CTS/Hermes. There is a strong requirement for system personnel overlap in responsibility to ensure continuity of function and documentation as staff leaves and is replaced throughout the life of the mission.

b) The above considerations apply equally well to spacecraft and ground station test personnel and operations. On CTS/Hermes there was a very strong collaboration between spacecraft subsystem design personnel and spacecraft test personnel. However, the involvement of the system's group with spacecraft test was minimal. As a result it was very difficult to obtain actual and specific design/test hardware information and to factor it into operations planning and software programming. Experience has shown that there is a real need for systems/operations interface with spacecraft/ground station design and test personnel.

c) A real scheduling/manpower problem occurred on the CTS/Hermes spacecraft test program particularly with the Engineering Model. The spacecraft test procedures were generally incomplete and too late for general dissemination and comment before the actual tests. At the very least, they had no system's group input. The whole test program was very success oriented in that not enough reaction time was scheduled before launch to replace or redesign equipment that had problems in test. Several eventual on-orbit problems that were observed (or should have been observed) during test and not satisfactorily acted upon were:

i) a NESA A anomaly

ii) Heat pipe freeze up

iii) RCS valve seating problems

iv) RCS latch valve opening under pressure problems

v) Transmitter B (TT&C) degradation during test

vi) Battery Reconditioning - UVS problems

vii) Battery B heat leak.

One critical problem that was caught in test, somewhat fortuitously, was in the Overvoltage Housekeeping Switch. It originally would not have closed (e.g. post-eclipse), thereby terminating the mission; a command function had to be added. Test planning, documentation and scheduling should be far enough in advance of launch, particularly for an experimental satellite, to allow reaction time and thoughtful test implementation and observation.

d) It was a conscious policy decision on CTS/Hermes to train the duty controllers on-the-job and to provide 24 hour a day coverage with 5 men in three eight hour shifts. Although this arrangement worked in a fashion, there were several undesirable consequences. As none of the chief duty controllers were active for the design or test phases of the S/C or software implementation, it was difficult to transmit more than cursory information to them. The chief duty controller accordingly had difficulty in training his duty controllers and bringing them "up to speed". There was no personnel overlap in this minimal panpower scheme let alone shift overlap to transmit S/C, G/S configuration information from one shift to another. Also as the Mission approached its several termination dates, it was extremely difficult to keep duty controllers on staff, thus aggravating an already tight manpower situation and compromising S/C health with new relatively untrained personnel.

There is also a general experience/qualification question to be answered before training and hiring duty controllers: what degree of man-in-the-loop S/C control should be left in the hands of what type of individual? With a highly sophisticated experimental satellite such as CTS/Hermes, it was found that by using technologist level duty controllers, brought on-board after launch, it was necessary to automate as much of operations as possible. This however created a boredom problem for duty controllers, especially on the second and third shifts.

It is highly recommended that eventual chief duty controllers be as experienced as possible and be introduced into future programs at least by the S/C test phase and be resident in the Systems Group. If 24 hour coverage is to be provided for future experimental satellites, a minimum of one chief plus six duty controllers should be required with four daily overlapping 8 hour shifts. The regular duty controllers should be allowed some pre-launch training time including real-time simulation runs.

e) One of the several problems resulting from incomplete initial on-orbit procedures and inexperienced duty controllers (particularly at the beginning of the Mission) was that there was no clear delineation of authority for specific events/procedures such as thermal control strategy, eclipse operations or battery management. It is therefore a recommendation that a clear delineation of responsibility and authority be made for all mission events and operations.

f) There was very little high-level rational thought given to all phases of CTS/Hermes computing requirements or software. Table 1 is a reasonably complete list of all the computational load from Program inception to Mission termination.

It is strongly recommended that all mission computing requirements be determined well before S/C test and before a ground station computing system is specified.

It is recommended, by using modern computing technology and analysis, to design/specify a Spacecraft Real-Time Computing System (SRTCS) which would allow for all required on-line, off-line computation to be done centrally at the ground station (including a real-time simulation capability). This could be achieved by using distributed processors under the control of an executive computer. The CRC/HCF, by example, is based on this distributed digital computing concept.

It is further recommended that the SRTCS be capable of:

i) processing all S/C telemetered data.

ii) providing all S/C command capability

iii) driving all real-time housekeeping displays

iv) processing all real-time S/C control and applications requirements

v) providing a Real-Time Simulation (RTS) capability or interfacing with a local RTS.

vi) providing background data base management for on-site, historical, faster than real-time data display.

vii) providing real-time graphics capability to aid in S/C attitude determination and subystem performance visualization.

viii) providing background processing capability such as orbit determination/prediction, etc.

g) Due to the lack of:

i) experienced system's personnel

ii) system/test/design interface

iii) resources

iv) ground station/simulation rehearsal

v) operations/operability input into detailed hardware and software design.

Detailed Operating Procedures (DOP's) and Non-Standard Procedures (NSP's) were generally incomplete by the start of the Mission On-Orbit phase and difficult to follow. Even after the procedures were eventually upgraded, several subsystems/operations (i.e., thermal, power, batteries, eclipse, attitude reacquisition, etc.) were very difficult to manage due to design hardware/telemetry operability deficiencies.

There, it is recommended that trained or experienced systems and operations personnel should have early and continuous interaction with hardware/software designers. Also preliminary DOP's and NSP's for all known events should be available for review and update well before launch.

It is further strongly recommended, that all procedures and operations personnel be tested at the Ground Station SRTCS using a Real-Time Simulation.

h) It is highly recommended that at the preliminary design phase, experienced and knowledgeable spacecraft design and operations personnel should assess the overall Mission Requirements with a view to specifying which functions should be automatic versus under manual operator control. It should further be decided whether automatic control functions should be incorporated on-board the spacecraft or in the ground control SRTCS.

Operational CTS experience indicated Automatic on-board control was a mixed blessing. While normal autonomous ACS pointing control was a decided advantage, ultimately the spacecraft was lost because automatic AFP/NESA-A action could not be inhibited.

Operations experience indicated that Automatic on-the-ground control was virtually impossible without truly secure and redundant telemetry. However, with truly secure telemetry it is possible to remove space certified hardware from the spacecraft and perform the function on the ground. This would allow relative flexibility in changing automatic control policy or modes based on operational experience.

It is strongly recommended that any automatic control mode on an experimental satellite must have a back-up manual or procedural control mode.

i) It is recommended that spacecraft subsytem design should proceed from an overall spacecraft system specification which clearly defines primary requirements and constraints. Detailed system and subsystem schematic diagrams should be prepared and updated constantly as the project proceeds rather than be initiated late in the project.

### 3.3.18 Off-Line Computing Hardware/Software

The generally slow turn-around time and awkward I/O transfers of the CRC, Sigman 9, batch-mode computer are generally documented in Section 18 of the Appendix. The major recommendations for non real-time computation are included in Section 3.3.17 of this report. The general preference is to have a capable, dedicated computer that is ideally located at the ground station or is integrated into the general ground station SRTCS.

# 4.0 CONCLUSION

## 4.1 Summary

The CTS/Hermes program achieved considerable success in spite of a large number of problems; throughout post-launch operations, there was a high risk of a significant reduction in system capability, finally realized in the loss of the satellite. The application of resources considerably in excess of those originally allocated, extraordinary efforts by all personnel involved in operations, and a certain amount of luck were necessary in meeting, and exceeding, mission objectives.

The negative aspects of CTS/Hermes on-orbit operations have been surveyed, and the results analyzed to provide recommendations of use in the design and operation of future spacecraft. A list of problems, causes, consequences and comments/recommendations related specifically to CTS/Hermes is given in the Appendix to this report. The final recommendations are given in Section 3 of this report; obviously, they are somewhat idealized, and their implementation will vary depending on detailed cost/benefit trade-offs specific to each application.

## 4.2 Acknowledgements

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TABLE 1: CTS/Hermes Mission Computing Load

| PHASE | HARDWARE | SOFTWARE | DESCRIPTION |
|---|---|---|---|
| 1) Subsystem and System Design | CRC Sigma 9<br>Vendor's Mainframe | Applications's FORTRAN Programming | Analysis and design programs for individual subsystems and for S/C system. |
| 2) Spacecraft On-Board Controller | RCA-DDA<br>(ACEA) | Hardware Non-programmable | ACEA-ACS subsystem autonomous attitude controller |
| 3) Spacecraft Test | PDP-8 | System Assembly and Machine Language Programming | Reduced and displayed S/C data during integration and test. |
| 4) Non Real Time (NRT) Simulation | Sigma 9 | SPARCON<br>SED Batch Mode<br>SED Interactive Mode<br>STREAK<br>ROBCON<br>Mainly FORTRAN Programming | Various versions of S/C dynamics and ground station emulation |
| 5) Real Time (RT) Simulation | Sigma 9 | Application's FORTRAN Extensive Modification to XEROX RT Operating System Required | - Spacecraft dynamics and subsystem simulation used to debug attitude acquisition and on-orbit procedures<br>- Used for analyst/controller training |
| 6) Ground Station Interface | HP2115/2116 | Assembly Language Programming | - Two way NASCOM link.<br>- RT Simulation - Sigma 9/Ground Station link.<br>- Data source to debug HP2100's. |
| 7) Attitude Acquisition On-Line Control | HP2100 A (no disc)<br>HP2100 B (disc) | - GCAP<br>- Proto On-Orbit System<br>- Non-standard Operating System<br>- Non-standard On-Orbit Configuration | - Real-time control of S/C during attitude acquisition<br>- Included several features of eventual On-Orbit system. |

TABLE 1: CTS/Hermes Mission Computing Load (cont'd)

| PHASE | HARDWARE | SOFTWARE | DESCRIPTION |
|---|---|---|---|
| 8) On-Orbit On-Line Control | HP2100 A/B (disc)<br>HP2100 B (disc)<br>HP21 MX (disc) | - On-Orbit System<br>- Extensive Modification of HP RT Executive and Operating System<br>- Modification of TELESAT OS | - Real-time S/C data reduction, monitoring and display<br>- Applications programs<br>- S/C command capability |
| 9) On-Orbit Off-Line Computation | Sigma 9 | Application's FORTRAN Programming | |
| a) S/C Data Reduction | Sigma 9 | TEODPS/CTSOPS<br>CALHIST | - Experiments archival data storage/display<br>- Operations data plotting routines |
| b) Orbit Determination and Events Prediction | Sigma 9 | GTDS<br>SED ORBDET | - Goddard very large orbit prediction program with ephemerides to predict solar/lunar interferences<br>- SED subset for rapid analysis of major operations |
| c) HP2100 Data Preparation | Sigma 9 | APPL-DAT | - Preparation of time sequenced messages and parameter values for the on-line HP2100's<br>- Transferred via paper tape |
| d) Performance, Analysis Programs | Sigma 9 | Application's FORTRAN Programming | - Thermal analysis<br>- Fuel budget<br>- ACS analysis<br>- RCS analysis<br>- Battery operations analysis<br>- Telemetry analysis |

# APPENDIX

## List of Undesirable Operations Events and Spacecraft Anomalies

(Derived from CTS/Hermes On-Orbit Operational Experience)

Abbreviations:

| | |
|---|---|
| UOE | Undesirable Operations Event |
| SCA | Spacecraft Anomaly |
| SHSPS | Suspected Hardware, Software, Procedure or System |
| OIP | Operation in Progress |

Subsystems:

1. SHF Transponder and Beacon
2. SHF Antennas
3. Telemetry, Tracking and Command
4. Power
5. Spacecraft Harness and Electrical Integration Assembly
6. Attitude Control
7. Structures and Mechanisms
8. Reaction Control
9. Apogee Motor
10. Thermal
11. SATE, TEC, S/C Charging, etc.
12. Transmitter Experiment Package
13. Ottawa Ground Station Non-Computing Hardware
14. Ottawa Ground Station Computing Hardware
15. Ottawa Ground Station Software
16. NASA/STDN Hardware/Software
17. Systems Planning, Test and Analysis
18. Off-line Computing Hardware/Software

Operations:

1. Steady-State Operations
2. On-Line Ranging Operations
3. Off-Line Orbit Determination/Events Prediction
4. Momentum Dump Operations
5. E-W Stationkeep Operations
6. N-S Stationkeep Special Operations
7. NESA Operations
8. Active Thermal Control Operations
9. Battery Recharge Operations
10. Battery Reconditioning Operations
11. Eclipse Operations
12. Longitude Change Special Operations
13. Attitude Recovery Non-Standard Operations
14. SHF Operations
15. Special Experiments Operations
16. Off-Line Sigma-9 Data Preparation Operations
17. CTS/Hermes Real-Time Simulation
18. Operations, Personnel, Schedules, Procedures
19. Other

Subsystem #1: SHF Transponder and Beacon

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 1.1 | 20W TWTA's (throughout life) | 1. Trip-offs while uplinking, believed to be due to overdrive.<br>2. Trip-offs following removal of uplink, believed due to arcing in the connector caused by outgassing. | a. Communications interruptions.<br>b. Cycling of tubes.<br>c. Complex command sequences.<br>d. Loss of essential data (when no telemetry). | 14 | 1. Better control of users. Possibly build-in limiters on-board.<br>2. Redesign connector. Better EMI protection on trip circuits. |
| 1.2 | 20W TWTA Cathode Heaters (throughout life) | 1. Cathode Heaters had to be on for ~3 minutes before HV on.<br>2. Switching off HV (by trip or ground command) also switched off the cathode heater. | a. Complex command sequences.<br>b. Risk of timing error damaging TWT.<br>c. Large number of cathode heater cycles. | 14 | 1. Include automatic sequencing/timing of commands (on-board or in ground S/W) - must be over-rideable.<br>2. Leave cathode heaters on. Care needed to avoid stripping cathode when HV off. Supply from batteries when array power unavailable. |
| 1.3 | Heaters/Temperature Sensors (throughout life) | 1. Temperature sensors not properly located. | a. Inadequate heater control - possible damage due to thermal extremes.<br>b. Excessive time and manpower required for analysis, scheduling, etc. | 8 | 1. Better system design, with heater and sensor locations integrated earlier in the design.<br>2. Possibly need thermostatically controlled heaters. |
| 1.4 | Beacon (throughout life) | 1. Unexpected (but within spec.) variations in frequency (rapid jumps and long term). | a. Time and manpower required for analysis.<br>b. Some difficulties for SHF beacon experimenters. | 1 | 1. More analysis/testing on expected operational behaviour (as distinct from meeting spec).<br>2. Better communications of such data to operations group. |
| 1.5 | Beacon (Eclipse exit, Day 073, 1977) | Difficulty in attaining high power due to either:<br>1. Ground equipment (e.g. locking on a side-band) or<br>2. Loss of gain in multiplier or<br>3. Too rapid switch-on of high power. | a. Time and manpower required for testing and analysis.<br>b. Potential loss of beacon (very unlikely). | 11/14 | Probably not a real problem<br>1. Upgrade ground equipment and operation.<br>2. More pre-launch testing/analysis of low temperature beacon behaviour.<br>3. Upgrade ground procedures/implementation. |

Subsystem #1: SHF Transponder and Beacon (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 1.6 | Beacon (throughout life) | 1. RF drive to beacon from Rx 1 ~2 dB low (within spec.). | a. Time and manpower required for testing and analysis. | 1 | Probably not a real problem<br>1. Better analysis/testing on expected operational behaviour (as opposed to meeting spec.). |
| 1.7 | TB1 and TB2 GRSS (Day 190, 1978) | 1. Fluctuations in signal strengths believed due to thermal effects on output coupler. | a. Time and manpower required for testing and analysis. | 1 | 1. Better analysis/design of coupler.<br>2. More testing of thermal effects. |
| 1.8 | Whole subsystem (throughout life) | 1. Various parameters (temperatures, currents, etc.) out of limits, but not indicative of real problems. | a. Time and manpower required for analysis.<br>b. Reduction in credibility of limit checks. | 1 | 1. Better communication of expected behaviour, particularly variation over lifetime, from design/test group to operations group.<br>2. More careful control of limits used in ground S/W. |
| 1.9 | TWT #2 PWM 50V Voltage (throughout life) | 1. Fluctuations in telemetry due to thermally unstable voltage divider. | a. Time and manpower required for analysis. | 1 | Known before launch<br>1. Do not fly unreliable sensors.<br>2. Better communication of such shortcomings to operations group. |
| 1.10 | Beacon and Spurious GRSS's (e.g. Day 207, 1979) | 1. Periodic drops in signal strength, at the same time as S-band SS dropped - probably due to ground equipment. | a. Time and manpower required for testing and analysis. | 1 | 1. Upgrade ground equipment and operations. |

Subsystem #2: SHF Antennas

| UOE/SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 2.1 | Antenna Steering Commands (throughout life) | 1. Complicated commands, difficult to relate to actual antenna movement required. | a. Command errors, including incorrect final position, incorrect rate of slew, hitting stops, etc. | 14 | 1. As was done on CTS, build simplified command structure in S/W including standard step size, slew rate, etc. for standard operations. Maintain general command capability for flexibility. |
| 2.2 | Antenna Steering (e.g. Day 303, 1977) | 1. Hit mechanical antenna stops with drive motors energized. | a. Possible failure of antenna motors and loss of steerability. Possible damage to antennas (unlikely). | 14 | 1. Ground S/W should include checks on all steering commands to avoid driving into antenna stops.<br>2. Incorporate an on-board switch to turn off drive motors before hitting stops. |
| 2.3 | Antenna Position Telemetry (throughout life) | 1. Telemetry resolution coarser than commandable step-size.<br>2. Telemetered positions varied (due to Encoder switching, thermal effects, etc.) with no change in true positions. | a. Confusion over differences between calculated and telemetered positions.<br>b. Occasional unnecessary extra commands sent to "correct" positions. | 14/1 | 1. Increase telemetry resolution.<br>2. Use digital telemetry rather than analogue for positions.<br>3. Perhaps use calculated position for ground display/control with internal S/W check against telemetered position.<br>4. System level study of step-size (commandable, observable and needed for pointing accuracy) required. |
| 2.4 | Boresight Antenna Positions (throughout life) (e.g. Day 036, 1976) | 1. Difficulties in obtaining antenna positions when boresighted at Ottawa.<br>2. Discrepancies between measured and predicted antenna positions when boresighted at Ottawa. | a. Confusion as to precise absolute pointing of antennas.<br>b. Possible small errors in antenna pointing. | 14/1 | 1. System level study required of causes, effects, significance, measurement, and correction of antenna pointing deviations from nominal. |

Subsystem #3: Telemetry, Tracking and Command

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 3.1 | Telemetry Transmitters (Tx B degradation started before launch and continued throughout life, with the first major drop on Day 108, 1976 and the first observed effect on Day 189, 1976; Tx A failure occurred on Day 259, 1976)<br><br>Note that, without this problem, the S/C probably would not have been lost (see consequences e, f and g in particular). | 1. Drastic reduction in Tx B output power.<br>2. Failure of Tx A.<br><br>This was the biggest problem on CTS/Hermes.<br>Tx A failure was abrupt and total.<br>Tx B behaviour was very complex; the effects on output power included a long-term decrease, and abrupt step-decreases of various magnitudes, some of which were reversible. In general, the Ottawa GRSS was either above the Ottawa G/S decommutation threshold (high power mode), or ~20 dB below threshold (low power mode). Low power mode occurred more and more often, for longer and longer periods as the mission progressed, and become essentially permanent in 1978. Some possible causes were:<br>a) Impedance mismatch caused by thermal expansion in the substrate.<br>b) High power stage ran hot, damaging some components.<br>c) Radiation damage to output transistors. | a) Loss or severe degradation of telemetry for a large part of the mission.<br>b) Significant increase in risks associated with all phases of the mission.<br>c) Major re-definition of all operations to reduce these risks and reduce/remove dependence on telemetry.<br>d) Dependence on NASA STDN stations for telemetry (latter half of mission).<br>e) Rapid loss of data, and loss of simultaneous use of both telemetry antennas, when attitude anomaly occurred.<br>f) Major problems in on-line and off-line interpreting of noisy data.<br>g) Loss of capability of automatic monitoring and commanding of the S/C, via ground computers, due to noisy data. | All | 1. System-level study required of on-board vs on-ground control, including reliability of ground station, uplink, downlink, transmitters, receivers, decoders, encoders, S/W, etc. This must be done in the conceptual design phase, with full recognition of the implications of making the S/C dependent on a ground loop vs the problems of inflexibility, reliability, qualification levels, etc., if the S/C is made totally self-contained.<br>2. System-level study required of the philosophy to be used in choosing redundant equipment, specifically whether redundant units should be generically identical, or not. Again this must be done in the conceptual design phase. |

Subsystem #3: Telemetry, Tracking and Command (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 3.2 | Telemetry Transmitters (throughout life) This item is a continuation of 3.1, but at a much more detailed level. Many of the points raised here should be covered if the recommendations of 3.1 are followed. | 1. Loss of good TM. | a. Array autotrack required (clock mode needed TM for daily updates). Risky due to lack of testing.<br>b. Many components subjected to temperature extremes because of:<br>i) Lack of TM to detect extremes.<br>ii) Modified heater operations due to lack of control TM.<br>iii) Minimizing heater switching to reduce risk of undetected incorrect state.<br>c. Command verification only available on some SHF subsystem commands.<br>d. Wheel speed measurement from nutation cone period (using SHF signals) required.<br>e. Monitoring of S/C attitude during major operations via SHF signals required.<br>f. Monitoring for attitude anomalies via SHF signals required.<br>g. Numerical data displays virtually useless due to noisy TM.<br>h. Much of the S/W for monitoring the S/C was virtually useless due to noisy TM. | All | 1. Drastically upgrade design/test/analysis of transmitters, partticilarly to cover the effects of thermal cycling<br>2. Provide a redundant telemetry link via the SHF (e.g. the beacon)<br>a. Arrays should be designed and tested to operate normally in auto-track.<br>b. Heaters should be thermostatically controlled.<br>c. Where possible, commands should be grouped, with one element of each group creating an effect observable on the ground without telemetry.<br>d. Detailed analysis of mass properties (including daily, yearly, and life-time variations) and predicted dynamic behaviour should be available to operations group.<br>e/f Perhaps additional beacons (SHF or S-band) should be provided to give direct, passive attitude information.<br>g. Maintain capability for displaying as much TM as possible in graphical form (SCR's, plotters, video graphics).<br>h. Possibly include sophisticated data filtering system in ground S/W. |

Subsystem #3: Telemetry, Tracking and Command (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 3.2 (cont) | Telemetry Transmitters (continued) | 1. Loss of good TM (continued). | i. Loss of uplink lock (and hence commandability) not observable due to noisy/no TM (mostly following attitude anomalies).<br>j. Problems with ranging system-turning on and off ranging tones directly impacted Tx B low/high power mode.<br>k. Loss of ranging capability when Tx B in low power mode.<br>l. Switching ground station (e.g. from Ottawa to NASA STDN station) frequently caused Tx B low/high power mode switching. | All | i. System-level study of integrity of command loop required, particularly to cover anomalous situations (attitude, telemetry, etc.).<br>j/k/l. Provide a redundant ranging system (via SHF).<br>j/k/l. Perhaps the prime ranging system should be independent of the telemetry system. |
| 3.3 | Telemetry Encoders (throughout life) | 1. Non-redundant Encoders. Used because there were not enough TM channels on one encoder to carry all required information. Encoder A was used primarily for launch, drift and attitude acquisition phases, and for special operations (e.g. M/D) on-orbit. Encoder B was used for most on-orbit operations. Most of the TM on structures, SAMA and SATE, plus most RCS temperatures one heater flag, and various other data were only on Encoder A. Most of the TM on SHF and TEP, plus six heater flags and various other data, were only on Encoder B. | a. Significant increase in complexity of ground S/W for processing TM.<br>b. Significant increase in complexity of thermal procedures due to lack of data.<br>c. Several components subjected to temperature extremes because of lack of data and/or errors in procedures/software/operations due to complexity.<br>d. Cycling of encoders required to obtain some data, particularly thermal (with an implied increase in the risk of failure).<br>e. Lack of data on which to base changes in operations (particularly for zero telemetry planning). | All | 1. System-level study required of precise TM requirements, including:<br>i) Is each piece of data useful and necessary.<br>ii) What word-length and repetition frequency is required for each piece of data.<br>iii) What overall bit-rate and frame length is required.<br>iv) How should resulting structure be implemented (digital vs analog words, processing in Encoder or at S/S level, subcommutation, etc.).<br>Many of the other recommendations for this subsystem would be covered by the results of this study. |

Subsystem #3: Telemetry, Tracking and Command (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 3.3 (cont) | Telemetry Encoders (cont'd.) | 1. Non-redundant Encoders (continued). | f. Confusion due to changes in telemetered data when Encoders switched (particularly wheel speed).<br>g. Variations in array stepping (when in clock mode) when Encoders switched.<br>h. Potential risk of loss of critical data if an Encoder failed. | All | 2. If there are not enough TM channels, selected data (e.g. temperatures) should be subcommutated. Care must be taken in selecting the data, and there may be weight/cost/reliability penalties, but non-redundant encoders are not an acceptable alternative.<br>3. System-level study required of the impact of using incompletely redundant units. |
| 3.4 | Telemetry Encoders (throughout life) | 1. Deviations from nominal in clock frequencies.<br>2. Differences between clock frequencies of two Encoders.<br>3. Variations in clock frequencies (short term at turn-on, daily, and long-term) believed due to thermal variations. | a. When in clock mode, the arrays had to be manually updated (~1/day), and Encoder switching caused significant variations in stepping.<br>b. Many TM parameters (particularly wheel speed) depended on clock frequency. Adjustment was complex, time-consuming, and prone to errors. | Various | 1. System-level study required of all causes and effects of deviations in clock frequencies from nominal.<br>2. Do not change clock source.<br>3. If possible, use more accurate, more stable clocks.<br>4. More testing/analysis on expected operational behaviour (as distinct from meeting spec.). Better communication of such data to operations group.<br><br>a. Arrays should be designed and tested to operate normally in auto track.<br>b. Build measurement of, and correction for, clock frequency effects in ground S/W. |

Subsystem #3: Telemetry, Tracking and Command (continued)

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 3.5 | Telemetry Antennas (e.g. Day 100, 1976) | 1. Lack of 4π Steradian coverage. | a. Loss of TM when attitude anomalies occurred, drastically increasing risks and complexity of recovery. | 13 | 1. Provide commandable 4π Steradian TM coverage (used only for attitude acquisition and re-acquisition to avoid interfering with other satellites). Perhaps automated if 4π Steradian earth sensors used. |
| 3.6 | Telemetry Data in General (throughout life) Most of these items are covered (in more detail and from a different point of view) in other subsystems. | 1. Ambiguous flagging of operating modes of Array Orientation Controllers.<br>2. Lack of cell-by-cell battery temperature and voltage.<br>3. Undersized pulse count registers (ACS and RCS).<br>4. Lack of resolution in SHF antenna position TM.<br>5. Undersized registers for array orientation angles.<br>6. Sub-commutated Transient Event Counter TM.<br>7. Sub-commutated TCU flags.<br>and many other problems related to the TM structure. | 1. Confusion and risk of incorrect mode.<br>2. Contributed to battery degradation.<br>3. Made performance analysis and prediction very difficult.<br>4. Confusion and occasional extra commands.<br>5. Uncertainty, particularly in attitude anomalies.<br>6. Lost a lot of data.<br>7. Erroneous indication when TCU's OFF. | Various | 1. See Recommendations of 3.3.<br>2. In general, sufficient data (e.g. temperatures) should have been sub-commutated to permit more complete TM in these (and other) areas. |

Subsystem #3: Telemetry, Tracking and Command (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 3.7 | S-band Downlink (throughout life) | 1. Loss of lock/noisy data due to interference from sun, or from other satellites.<br>2. Loss of lock due to loss of uplink lock, and difficulty in re-acquiring lock after loss (particularly following attitude anomalies).<br>3. Unexpected variations in GRSS - possibly due to atmospheric effects, ground equipment, S/C charging, etc. | a. Loss of critical data (usually for short times), increased risks, extended re-acquisition times, etc. | All | 1. These effects must be included in study of Recommendation 1 of 3.1. Possibly need sophisticated signal/data filtering system on ground.<br>2. Free-running S/C Tx frequency should be closer to locked frequency. Perhaps a better sweep system is required. |
| 3.8 | S-Band Uplink (throughout life) | 1. Loss of lock due to station handovers, ground station power failures, incorrect updating of ground antenna, S/C antenna null (following attitude anomalies) and (possibly) unknown other causes. | a. Loss of commandability.<br>b. Loss of telemetry (see 3.7). | All | 1. Improve station handover procedure.<br>2. Improve protection against effects of G/S power failures.<br>3. Improve prediction and implementation of G/S antenna positioning. Possibly use auto-track. |
| 3.9 | NASA STDN Command Link (throughout life) | 1. Occasional commands not executed. | a. Potentially catastrophic. | Various | 1. Upgrade check-back system between commands transmitted by ground station and those received by support station. |

Subsystem #3: Telemetry, Tracking and Command (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 3.10 | Commands in general (throughout life) Most of these items are covered (in more detail and from a different point of view) in other subsystems. | 1. Complex attitude bias commands.<br>2. Complex SHF antenna steering commands.<br>3. Time delays required between SHF transponder commands.<br>4. Multiple Thermal Control Heater commands.<br>5. Linked RCS Heater/Offset Thruster commands.<br>6. Multiple purpose commands in general.<br>7. Inability to command PRC Parameter Set #4 directly.<br>8. Several heaters should have been broken up into several separately commandable parts (if enough command channels had been available)<br>and many others related to command structure. | a. Relatively minor command errors occurred. Potential major command errors.<br>b. Complex operations instructions and checking required.<br>c. Some operations were compromised, particularly thermal. | Various | 1. System-level study required of optimum command structure, including simplicity and safety of operator instructions, manipulation in ground S/W vs in S/C H/W, use of value commands, inclusion of timing capabilities, effects of multi-function commands (particularly in non-standard situations), etc. Some of the goals should be:<br>a) Operator inputs must be simple and easily understood.<br>b) Unnecessary cycling of on-board equipment should be eliminated.<br>c) Meaningful checks on safety and appropriateness of commands should be included.<br>d) All potentially desirable S/C states should be commandable.<br>The emphasis should be on operability, particularly over the long term, and including non-standard situations.<br>2. To reduce number of commands required, increase use of value commands. |

Subsystem #3: Telemetry, Tracking and Command (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 3.11 | Command Link (e.g. Day 077, 1978) | 1. Commands not executed due to ground equipment configuration (e.g. 70 kHz off) and/or problems. | a. Relatively minor effects (e.g. O/T armed and AFP Enabled through a sun interference). Potentially severe. | Various (e.g. 7) | 1. Build in checks on all ground equipment, with feed-back to computer.<br>2. Upgrade ground operations. |
| 3.12 | Ranging System (throughout life) | 1. Discrepancies between impulse delivered to S/C (e.g. during E-W S/K) as calculated from orbit determination and from RCS performance data. (Discrepancies exceeded estimated errors) Origin uncertain. | a. Minor uncertainties in orbit predictions.<br>b. Major uncertainties in RCS performance analysis and predictions. | 2/3 | 1. Upgrade on-line ranging system (e.g. measurement of time delays), off-line processing of data (particularly error estimates), and RCS performance prediction.<br>2. Early recognition of the importance of accurate measurement of delivered impulse for RCS performance analysis/ predictions. |

Subsystem #4: Power

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 4.1 | Battery Capacities (throughout life)<br><br>This was one of the major problems on CTS/Hermes.<br><br>Although not explicitly included here, this problem was considerably magnified by the degradation/loss of telemetry (see 3.1).<br><br>Note that these problems contributed significantly to the loss of the S/C (see consequence e) | 1. Large-scale, unequal degradation in battery capacities, largely irreversible, over life.<br>2. Unpredictable cell drop-outs (during eclipses and reconditionings).<br>Believed to be due to:<br>3. Subjecting flight batteries to harsh prelaunch environment (test and storage).<br>4. Overheating of batteries due to apogee motor heat soak-back.<br>5. Overheating of Battery B due to heat path to aft platform (mispositioned battery mounting post).<br>6. Overheating of both batteries, and excessive thermal gradients between batteries and between cells in each battery, due to inadequate thermal analysis and design.<br>7. Inadequate daily charge/discharge regime, particularly:<br>a) Long open circuit stand times.<br>b) Long periods of very low discharge (through the Common Diode Rail).<br>c) Charge currents too low.<br>d) Uncertain definition of end of charge. | a. Uncertainties in predicted capacity for eclipses, and following attitude anomalies.<br>b. Generally too low a capacity to sustain full loads for eclipses and after attitude anomalies (later in life).<br>c. Load shedding required during eclipses - increased risk of failure of various components.<br>d. High risk of undervoltage trip towards the end of eclipses and during attitude anomalies.<br>e. Highly likely that UVS trip occurred shortly after attitude anomaly at S/C loss.<br>f. Excessive manpower and time required to analyse and manage batteries.<br>g. Complex operations required, causing occasional errors (which further degraded the batteries). | 9/10/11/ 13 | 1. Include better estimate of degradation effects in sizing batteries.<br>2. Possibly use a shunt-regulated system, perhaps using array orientation to control heat dissipation (but note possible conflict with ACS).<br>3. Possibly use chemically different batteries (e.g. metal hydride), particularly for longer life satellites.<br>4. Do not integrate flight batteries on S/C until last possible moment (use E/M batteries, or other spares, for pre-launch S/C level testing wherever possible). Locate batteries on S/C for easy access/removal/replacement.<br>5. Drastically upgrade thermal design/analysis/testing of battery system (single node approach is not adequate). Possibly use heat pipes to minimize temperature differences between cells and between batteries. Possibly use thermostatically controlled heaters and louvres to maintain battery temperatures between 0°C and 15°C. |

Subsystem #4: Power (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 4.1 (cont) | Battery Capacities (continued) | Causes of capacity loss (continued)<br>8. Inadequate reconditioning regime, particularly:<br>a) Inability to achieve less than 0.9 volts/cell.<br>b) Low discharge rate.<br>c) Low recharge rate.<br>d) High temperatures.<br>9. Uneven sharing of loads by batteries causing further degradation of the weak battery, causing worse load-sharing, etc.<br>10. Inadequate current monitoring capability, particularly at low discharge rates, due to:<br>a) non-redundant Encoders,<br>b) inaccurate sensors,<br>c) inadequate calibration.<br>11. Inadequate voltage monitoring capability, particularly:<br>a) No voltage telemetry below 0.8 volts/cell.<br>b) No indication of voltage spread between cells, or of voltage of lowest cell. | h. High risk of cell reversal in reconditioning due to spread in cell characteristics. (Potentially catastrophic failure when recharged) - required continuous monitoring by battery experts.<br>i. Self-discharge of batteries (due to build-up of internal impedance) causing further uncertainties in recharge requirements. | 9/10/11/13 | 6. Upgrade thermal design/analysis/testing of all components interacting with the batteries, and do not fly changes without complete thermal analysis.<br>7. Charging capabilities should include:<br>a) A high rate charge (~C/3) and either<br>b) A voltage controlled, temperature compensated taper charge, with commandable voltage level.<br>or<br>c) A "trickle" charge, essentially to maintain a constant bias on the batteries when not in use.<br>Note that b) or c) would operate at all times array power is available, and would normally supply the C.D.R.<br>8. A reconditioning system is mandatory. It should include:<br>a) A high rate discharge (~C/3) and<br>b) A low rate discharge (~C/50) to be used below 1 volt/cell.<br>c) Capability for discharge to at least 0.6 volts/cell.<br>9. If at all possible, battery voltage and temperature TM should be cell by cell. In any case, battery voltage TM must cover at least 0.6 volts/cell (preferably 0.0 volts/cell) to 1.6 volts/cell). |

Subsystem #4: Power (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 4.1 (cont) | Battery Capacities (continued) | Loss of Capacity (continued) | | 9/10/11/13 | 10. A major improvement in battery operations would result if the capability existed for cell-by-cell shorting. Essentially complete reconditioning could then be achieved and, when not required (i.e. non-eclipse), some of the batteries could be stored in a benign mode. Major problems exist, however, in weight, cost, reliability, telemetry and command requirements, etc.<br>11. Either<br>a) Operate batteries entirely separately (probably not feasible from a S/C safety point of view).<br>or b) Provide a means of adjusting load sharing between them (e.g. on adjustable isolating impedance).<br>12. Charge and discharge current sensors should:<br>a) cover the full range of currents,<br>b) provide high accuracy for low level currents,<br>c) be continuously available (i.e. do not use non-redundant Encoders). |

Subsystem #4: Power (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 4.2 | Battery Management (throughout life) | 1. Virtually full-time battery specialist support required to monitor battery behaviour, schedule charge cycles, schedule and monitor reconditioning cycles, and predict future performance/behaviour.<br>2. Reconditioning times were severely constrained because of possible overheating/delamination of discharge resistors if used when in sunlight. This caused major scheduling/manpower problems, particularly with bad/non-existent telemetry.<br>3. Battery operations in general were unique to these batteries and varied literally day by day.<br>4. The battery charge controllers could not handle high voltage, high current charging. | a. Limited resources severely strained.<br>b. Virtually total dependence on specific individuals. Potential for major problems if such individuals unavailable.<br>c. Complicated procedures causing occasional errors (e.g. automatic switch from C/10 to C/20 at high charge voltage). | 9/10/11/13 | 1. Using analysis/test/simulation/experience/etc., better definitions are required (pre-launch) of:<br>a) Battery capacity,<br>b) A fully-charged battery.<br>c) How to determine when a battery is fully charged,<br>d) Expected changes in battery capacity with life, use, etc.<br>2. Battery management can be significantly improved by:<br>a) Possibly including on-board (programmable) microprocessors.<br>b) Upgrading ground S/W and procedures, and operator training.<br>c) Positioning and qualifying reconditioning resistors to be usable at all orbit slots.<br>d) Designing charge controllers to handle all required charge current/voltage combinations.<br>e) Provide command capability to override all automatic switches. |

Subsystem #4: Power (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 4.3 | Battery Under Voltage Sensor (throughout life, but particularly in 1978 and 1979 eclipse seasons)<br><br>Note that these problems contributed significantly to the loss of the S/C (see consequences c and d). | 1. UVS was not overrideable - even when disabled, UVS trip on one battery would enable UVS on the other battery.<br>2. Voltage for UVS trip was fixed.<br>3. UVS trip caused loss of virtually all S/C information (TM, S-band carrier, 200W TWT). Since array power loss was essentially a prerequisite for UVS trip, the remaining information (20W TWT, SHF beacon) was also unavailable.<br>4. Recovery from UVS trip was extremely complex and ill-defined primarily due to the interaction between 1 (above) and parallel, mismatched batteries, giving a high probability of multiple UVS trips.<br>5. UVS was enabled whenever a battery was put on charge. | a. High risk of UVS trip particularly late in life when batteries had degraded in voltage and capacity.<br>b. Lack of access to low voltage capacity late in life (required eclipse load sheds, etc.).<br>c. High probability that UVS tripped shortly after attitude anomaly at S/C loss, and that S/C could have been recovered otherwise.<br>d. Low probability of recovery from UVS trip.<br>e. Complex command sequences, with potential for error. | 10/11/13 | 1. Provide command capability to completely override all automatic switches.<br>2. UVS protection is necessary, but a system level study is required including:<br>a) What is being protected (S/C vs batteries).<br>b) What components should be switched off by UVS trip.<br>c) Under what circumstances should UVS trip. Under what circumstances will undesirable trips occur.<br>d) How to improve flexibility of UVS systems (e.g. ground control of trip voltage and of components switched off by trip).<br>e) How to recovery from UVS trip, etc.<br>This study must take place before the UVS is designed and implemented.<br>3. Provide command capability to change UVS trip voltage to allow for battery degradation.<br>4. Leave (at least) S-band carrier on after UVS trip.<br>5. Greater care should be taken in desiging multi-function commands (see 3.10, Recommendation 1).<br>6. Improve battery system design, particularly separability (see 4.1, Recommendation 11). |

Subsystem #4: Power (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 4.4 | Experiments Power Converter (EPC A failed on Day 064, 1976. Damage probably occurred in earlier eclipses) | 1. EPC A failed - unable to supply regulated voltages required by SHF components.<br>Believed to be due to:<br>2. Very large and rapid thermal transients of the arrays at eclipse entry and exit caused much larger and more rapid voltage transients than the automatic protection circuits (OVC/UVC) could handle. Overvoltage at eclipse exits damaged one or more of the OVC/UVC relays.<br>3. The internal coils of the high power OVC/UVC relays were not properly heat sunk, leading to further damage.<br>4. The damaged relay opened anomalously (power lost on 76V bus, but not on EPC) then closed again (array collapsed due to 76V bus load).<br>5. A reverse surge through the EPC current limiter (from capacitance downstream of the EPC to the 76V bus loads) damaged the limiter so that normal current flow through the EPC was permanently inhibited.<br>6. Pre-launch test data indicated weakness in the relay that failed (not recognized until post-anomaly analysis). | a. High risk of loss of all SHF communications (if redundant EPC had failed).<br>b. Complex operations and commanding sequences required to protect EPC B. Specifically automatic OVC/UVC could not be used for eclipse operations.<br>c. Large amounts of time and manpower required for analysis and testing of problem, verification of safety of using EPC B in eclipse season, and development of procedures for using and protecting EPC B.<br>d. Suspension of all SHF operations for two eclipse seasons. | 11/14 | This problem proved the validity of a) carrying redundant units and b) being able to override automatic switching.<br>1. Drastically upgrade analysis/testing of transients (thermal and power) on light-weight arrays, particularly at eclipse entry and exit.<br>2. Upgrade thermal design/testing of high power relays.<br>3. Upgrade analysis of test data on critical components.<br>4. Upgrade failure modes and effects analysis. This might have indicated that series relays should not be used in high power circuits.<br>5. Upgrade analysis of potential sneak paths, particularly in high power circuits. |

Subsystem #4: Power (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 4.5 | Housekeeping Power Converters (throughout life) | 1. Lack of accurate data on power required for various loads (particularly converter losses).<br>2. Lack of data on behaviour of power converters at low voltages. | a. Uncertainties in predicting effects of load sheds (in eclipses).<br>b. Time and manpower required for post-launch S/W changes to correctly calculate converter power usage (particularly MWC).<br>c. Power/thermal status unknown after UVS trip (e.g. at S/C loss). | 1/11 | 1. Upgrade test measurement of power usages, as functions of currents, voltages, temperatures, duty cycles, etc. Better communication of this data to operations group.<br>2. Pre-launch testing should extend beyond expected performance region. |
| 4.6 | Solar Array Power (throughout life - loss of 15% of array power occurred on Day 160, 1976) | 1. Loss of ~15% of experiments array power, believed due to arcing on the pallet diode board.<br>2. Lack of accurate array temperature data due to:<br>a) Only temperature data was part of SATE and was lost with SATE.<br>b) Dummy cell over temperature sensor was thermally different from main power cells.<br>3. After SATE failed, measurement of array power capacity required successively loading the bus.<br>4. Solar cell degradation. | 1. Potential constraints on experiments use.<br>2. Inaccurate data on array thermal behaviour. Complicated attempts to measure array power capacity, etc.<br>3. Complex operations required. Risk of overloading bus, causing collapse of arrays, leading to trip-offs of various components under full power. Large uncertainties in results.<br>4. Steady decrease in array power - requires periodic array power capacity measurements. | 1 | 1. Improved protection against S/C charging and its effects (see Subsystem #11).<br>2. Provide temperatures sensors on main power array cells, as part of H/K, not experiments.<br>3. Provide redundant direct means of calculating power capacity as part of H/K, not experiments.<br>4. Not really a problem, as both the effect and its magnitude proved predictable. Note that arrays must be sized including this (particularly for long-life S/C). |

Subsystem #4: Power (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 4.6 | Solar Array Power (continued) | 5. Power and H/W wasted in<br>a) Jettison of part of body array in attitude acquisition.<br>b) Power from remaining body arrays not usable.<br>6. Under no load, cold body arrays supplied high voltage. | 5. Potential decrease in weight. Potentially simpler thermal design (if JBSA's retained, or not there in the first place). Potential increase in available power.<br>6. H/K bus switch remained open post-eclipse. Manual closing was risky due to lack of array voltage TM. | 1 | 5. System level study required of body array when on-orbit, including:<br>a) Optimizing use of H/W,<br>b) Potential for providing power when prime array power unavailable.<br>c) Other impacts on prime system (see 6).<br>6. Either:<br>a) break connection between body array and power S/S after deployment of main arrays,<br>or b) clamp the voltage of the body arrays below the H/K OVC level.<br>In any case, provide telemetry on array voltage (in addition to bus voltage). Note that the command to close the H/K bus switch was a late addition on CTS/Hermes. Without it the S/C could have been lost much earlier - another example of the need to provide override capability on automatic switching. |

Subsystem #4: Power (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 4.7 | Secondary Power Converter (Day 273, 1976 Day 079, 1977) | 1. SPC-A tripped off. Possibly due to S/C charging and/or problems in SATE (particularly since there were no trips after SATE failed). | a. Loss of all secondary modules (hence encoders, hence telemetry).<br>b. Uncertain secondary module configuration when SPC turned on.<br>c. RCS Heaters E, F and G turned partially on.<br>d. Potential damage to solid state switches controlled by secondary modules.<br>e. Complex and uncertain (see b) operation for recovery, with associated risk of error. | | 1. Upgrade protection against S/C charging (see Subsystem #11).<br>2. Wherever possible, power-on resets should be applied to all components downstream of a power supply before power is supplied to them. Possibly power-off resets of some sort could be used instead.<br>3. Do not use logic switches where power controlling the switch can be off at the same time as power through the switch is on. Either:<br>a) Use latching relays or,<br>b) Use a common power source.<br>4. Turning off RCS and SAMA secondary power (by command or trip) should have turned off the appropriate 27.5V power supply.<br>5. Where a specific turn-on sequence is required, it should be automated either on-board or in ground S/W (e.g. RCS 27.5V on before RCS secondary module on).<br>6. Possibly isolate Encoder (as well as Tx) power supplies. |

Subsystem #4: Power (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 4.8 | Eclipse Durations | 1. No allowance was made in design, test, or planning for long eclipses of the sun by the moon (theoretically up to 3 hours from entry into partial to exit from partial). | a. Potentially catastrophic if power available from arrays drops too much for too long, or if temperature of arrays raises voltages above OVC point for too long. | 11 | Did not occur, but is a possibility.<br>1. Upgrade predictions of possible eclipse occurrences. Detailed analysis of worst case required.<br>2. Design thermal/power subsystem (particularly batteries) to handle this worst case. |
| 4.9 | Whole Subsystem (throughout life) | 1. Erroneous data displayed. In particular, battery discharge currents showed non-zero values when batteries were on charge, and these values varied depending on charge rate, etc. | a. Confusion in operations, and reduced efficacy of some S/W. | All | 1. Sensors must provide consistent outputs.<br>2. Accurate and complete calibration data must be supplied to operations group well before launch.<br>3. Calibration S/W must be flexible enough to include:<br>a. A variety of functional forms.<br>b. The effects of other parameters (e.g. temperatures) on the sensor outputs. |

Subsystem #5: Spacecraft Harness and Electrical Integration Assembly

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 5.1 | S/C Wiring Harness | 1. No obvious direct problems<br>- perhaps some S/C charging problems (see S/S #11) | a. See S/S #11 | 1 | 1. Possibly needed improved EMI protection. |
| 5.2 | EIA | 1. No obvious direct problems<br>- heater commands and temperature data processed in this unit should have been upgraded (see S/S #3 and #10)<br>Also TEC included in EIA (see S/S #11) | a. See S/S #3, 10 and 11<br>b. It is possible that loss of SATE and SPC A trips resulted from occurrences in TEC/EIA. | 1/8 | 1. Possibly subcommutation of thermal data should have been built into EIA.<br>2. All heaters should have been separately commandable - could have been implemented in EIA.<br>3. Possibly need improved EMI protection. |

Subsystem #6: Attitude Control

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 6.1 | Non-Spinning Earth Sensor A<br><br>(Turn-on Anomalies:<br>1 on Day 100, 1976<br>3 on Day 101, 1976<br>1 on Day 143, 1976<br>1 on Day 120, 1979<br>Running Anomalies:<br>Day 227, 1977<br>Day 322, 1977<br>Day 120, 1979<br>Day 237, 1979<br>Day 330, 1979)<br><br>This was one of the major problems on CTS/Hermes.<br><br>Although not explicitly included here, this problem was considerably magnified by the degradation/loss of telemetry (see 3.1).<br><br>Note that, without these problems, the S/C would not have been lost (see consequence d).<br><br>Several other items (e.g. 6.2) relate directly to these problems. | 1. Anomalous behaviour after some turn-ons:<br>a) Scan output saturated for ~25 seconds after turn-on (normally essentially constant at ~20% of saturation),<br>b) Scan output saturated after warm-up completed (~80 seconds after turn-on) (normally measured pitch error),<br>c) Cross-scan output saturated after warm-up completed (normally measured roll error).<br>d) Earth presence flag remained high after loss of earth from field of view (normally low during warm-up period, and when earth not in field of view).<br>Note that when NESA-A was on, and its EP high, NESA-A scan controlled pitch and, when NESA-B was off or its EP low, NESA-A cross-scan controlled roll-yaw.<br>2. Running anomaly:<br>a) During normal operations (both NESA's on), NESA-A scan and cross-scan outputs occasionally step-changed to saturation, and remained there.<br>b) Earth presence flag remained high after loss of earth from field of view.<br>The two anomalies are believed to be related. Possible causes are: | a. Automatic Failure Protection (AFP) tripped causing<br>i) main tank latch valves closed,<br>ii) switch to redundant ACE and MWC.<br>iii) After 5 second time delay, ACE activated in CWS (constant wheel speed) mode. Wheel speed dropped ~15 rpm, then stabilized; S/C pitch rate stabilized at ~3°/minute.<br>b. Pitch rate caused NESA B to lose the earth. Saturated NESA-A cross-scan caused roll-yaw thrusters to fire at high rate with long on-times, unexpectedly causing:<br>i) Large unpredictable changes in pitch rate,<br>ii) Large-scale roll-yaw coning and precession.<br>c. Pitch rate/coning/precession caused loss of array tracking, hence loss of array power and UVS trip (see S/S #4).<br>d. Loss of S/C (Day 330, 1979) due to:<br>i) Loss of all S/C information.<br>ii) Loss of power to components necessary for recovery. | 1/7/13 | 1. Minimize use of moving parts in <u>all</u> critical components.<br>2. <u>Do not</u> fly components that fail <u>during</u> pre-launch testing. If it is essential to refurbish and fly components after they have failed, time and resources must be available so great care can be taken to ensure that the causes of the failure are completely understood and corrected. Much better to have fully qualified spares available.<br>3. Do <u>not</u> fly partially redundant <u>units</u>. Where incomplete redundancy is forced (e.g. by weight considerations):<br>i) Design, manufacture and testing of units must be drastically upgraded.<br>ii) <u>a complete and rigorous FMEA is a necessity</u> to determine whether this results in unacceptable risks.<br>iii) Detailed recognition/recovery/work-around procedures must be developed (before launch) to cover any failures.<br>4. Automatic failure protection against attitude anomalies is essential. However, AFP trip must totally inhibit <u>all</u> thrusting, and should <u>be</u> designed to minimize resulting S/C rates. Specifically, on CTS/Hermes, |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 6.1 (cont.) | NESA-A Anomalies (continued) | 3. Sticking of the scanning mirror, either complete, or on a high percentage of scans, (Note that the mirror on this NESA stuck during pre-flight testing). Sticking may have been related to thermal distortion/unstable flex pivots/ contaminants/motor problems/ overheating.<br>4. Possibly some form of EMI and/or electronics failure/anomaly. May have been triggered by S/C charging sun reflections, SHF radiation, etc.<br>5. It appears likely that there were correlations between the occurrences of NESA-A anomalies and:<br>i) NESA-A temperatures<br>ii) Sun position relative to the S/C.<br>6. It is possible that the anomalies were induced, or at least their probability increased, by excessive NESA-A power cycling. | d) (continued)<br>iii) Loss of thermal dissipation causing S/C to become too cold to function.<br>Note that all of a,b,c and d occurred only on Day 330, 1976. The dynamic mode resulting from other anomalies were (largely fortuitously) such that array tracking was not permanently lost. In particular, if the roll-yaw thrusters were inhibited before NESA-B lost the earth, the pitch rate remained low, and no coning/precession occurred.<br>Secondary Consequences<br>e. Loss of SHF communications (for up to 1 day for each anomaly except last).<br>f. Extremely complex and uncertain recoveries, with excessive use of manpower and other resources.<br>g. Excessive manpower, time and computing resources required to:<br>i) Analyse anomalies.<br>ii) Develop and test procedures to minimize occurrences of anomalies and to recover from anomalies.<br>iii) Train operations personnel in use of new procedures. | | 4. (continued)<br>i) AFP trip should have inhibited the ACE outputs to the O/T (could have been implemented in automatic ground S/W if TM were usable).<br>ii) The time delay before initiation of CWS mode mode should have been much shorter, and the tachometer bit-size much smaller.<br>5. Provide an indpendent secondary attitude sensing system. If the prime system indicates an anomaly, the secondary system should be checked, and its outputs used for attitude control (possibly degraded) if it indicates the anomaly is in the prime sensor, rather than in the S/C attitude. It may be necessary to use several sensors with a "voting" system.<br>6. Provide an automonous on-board attitude re-acquisition capability.<br>Note that 5 and 6 (above) require very careful system-level design, including FMEA, reliability, etc.<br>7. Upgrade pre-launch testing of essential sensors, particularly for effects of thermal gradients and cycling, and for durability. |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
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| 6.1 (cont) | NESA-A Anomalies (continued) | | Secondary Consequences (cont.)<br>h. Introduction of operations that involved:<br>i) Higher risks (e.g. flying through NESA-A moon interferences).<br>ii) Complex scheduling (e.g. NESA-A turn-ons).<br>iii) Excessive use of specialists (for all NESA-A operations).<br>i. Potential for catastrophic failure when AFP disabled (completely uncontrolled pitch rate if NESA-A anomaly occurred). | | |
| 6.2 | NESA Switching (throughout life)<br><br>Note that many of these problems are closely related to 6.1, as causes or effects. | 1. To remove a NESA from the attitude control loops it was necessary to turn it off (e.g. to avoid sun interference on the NESA causing loss of attitude lock).<br>2. After the NESA-A turn-on anomaly occurred, NESA switching was reduced to an absolute minimum by:<br>a) flying through NESA-A moon interferences,<br>b) leaving both NESA's on through NESA-B interferences (but inhibiting the effect on the attitude of the NESA-B outputs),<br>c) reducing the safety margins on the NESA sun and moon interference zones. | a. Excessive cycling of NESA's; this probably contributed to the NESA-A anomalies (6.1).<br>b. High risk turn-ons of NESA-A, requiring specialist assistance and complex scheduling and operations.<br>c. Flying through NESA-A moon interferences (to reduce cycling) resulting in large-scale attitude perturbations (up to 2°), risk of attitude control loss, complex operations, and the need for specialist assistance. | 7 | 1. The choice of which sensor outputs are used to control the attitude should be made by logic switching, not power switching.<br>2. Passive, benign, long-term stable modes should be designed into all attitude control loops (e.g. roll-yaw control with O/T inhibited on CTS/Hermes). Specifically, in pitch, CWS mode is an essential minimum, but should be modified to drastically reduce the resulting pitch rate such that earth-lock is maintained (over e.g. the duration of sun interference) with no sensor inputs to the control loop. Some possibilities are using a rate integrating gyro, applying an averaged duty cycle to the wheel, etc. |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
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| 6.2 (cont) | NESA Switching (continued) | 3. The number of NESA interferences was not properly included in mission planning (particularly moon interferences). The effects were not well understood, and operations to deal with them were not optimized until well after launch. | d. Cancelling AFP during NESA-B sun interferences, with potential for S/C loss if an anomaly occurred, and complex operations required.<br>e. Decreased safety in ignoring marginal interferences.<br>f. Excessive time and manpower to design and test new procedures. | | 3. Sensors should have built-in capability for ignoring interference effects (e.g. radiance limiters to cut out sun).<br>4. Upgrade pre-launch prediction of interference occurrences and effects, and system-level analysis of operations to deal with them. |
| 6.3 | Pitch Transients (throughout life) | 1. "Pitch Glitches"-small (up to 0.2°) short-term (~2 minutes) transients in pitch, more or less at random throughout life.<br>Possible causes are:<br>2. Variations in wheel drag torques due to variable bearings, thermal effects on lubricants, etc.<br>3. Caging instability.<br>4. NESA problems.<br>5. EMI/electronics problems in control loops.<br>6. Anomalous torques from pitch thrusters (see 8.1).<br>7. Some of the glitches may have been due to interaction between register overflow in control loops, array stepping, and flexible array dynamics. | a. Minor attitude perturbations. Time and manpower for analysis, testing, etc. | 1 | 1. Upgrade pre-launch testing, analysis and Q.A. on wheel, particularly bearings/lubricant. Note that:<br>i) No way has yet been found to eliminate cage instability in wheel manufacture but<br>ii) Methods have been devised for detecting such instabilities, so that suspect wheels can be avoided.<br>2. Upgrade detailed analysis/simulation of expected pitch loop behaviour; specifically, more detailed modelling of array stepping effects is required.<br>3. Reduce array step-size (in auto-track mode). Perhaps some form of essentially constant torque drive is feasible. |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
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| 6.4 | Pitch Transients (major operations) | 1. Significant (~0.5°) pitch transients of up to 5 minutes duration during momentum dumping, major arrays slewing and other major events.<br>Basically due to an overly sluggish pitch controller which was the result of:<br>2. Fixes incorporated to compensate for a significant under-estimate of time delay in NESA's used in early control system design.<br>3. Assumption of very low damping in arrays in control system design. | a. Predicted pre-launch. Some impact on SHF communications. Could be of major significance for an operational S/C.<br>b. In general, the pitch loop was significantly "sloppier" than necessary (i.e. a tighter design of the control loop would have reduced both magnitude and duration of transients).<br>c. Time and manpower required for analysis and simulation. | 4/5/6/ 11/12/15 | 1. Significantly upgrade modelling of sensors early in the design of control loops.<br>2. Design control loops to handle wide dispersions in assumed parameter values.<br>3. Design control loops to handle a much wider range of damping in flexible appendages, perhaps using programmable microprocessors on-board.<br>4. Develop a system for more accurately calculating or measuring flexible body damping pre-launch.<br>5. Perhaps build in mechanical dampers of flexible appendages to provide known, minimum damping. This is, however, inefficient and inflexible compared to 3 (above).<br>6. Upgrade analysis of expected performance (as opposed to meeting spec.) and improve communication of such data to operations group. |

Subsystem #6: Attitude Control (continued)

| UOE/SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
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| | | DESCRIPTION | CONSEQUENCES | | |
| 6.5 | Roll-yaw Effects of Array Slewing | 1. Roll-yaw effects of normal (essentially simultaneous) array slewing up to 0.1°.<br>2. Slewing of a single array created roll-yaw cone of 0.4° half-cone angle. Analysis showed that a longer slew could have given up to 2° half-cone angle. | a. Time and manpower required for analysis and simulation.<br>b. Negated some operational methods of protecting against, and recovering from, UVS at eclipse exit. | 4/5/6/ 11/12/15 | 1. Upgrade detailed analysis/ simulation of coupling between roll/yaw and pitch through arrays.<br>2. Pre-launch analysis/design of control loops should include non-standard array operations. |
| 6.6 | Attitude Effects of Major Events<br><br>Note that neither the move West, nor N-S S/K were included in the original S/C design and operations planning. | 1. Large roll-yaw errors (~1-2°) resulted from large-scale E-W (for move West) and N-S (for inclination control) thruster firings.<br>2. Large wheel-speed changes (up to 600 rpm) resulted from the same firings.<br>3. Large yaw errors during N-S S/K caused major E-W effects on the orbit.<br>These effects were caused by:<br>4. Thruster misalignments.<br>5. The variable position of the S/C centre of mass (daily and over life).<br>6. Thruster mis-match and under-performance (particularly during N-S S/K).<br>7. Inadequate yaw sensing/control (particularly during N-S S/K).<br>8. Plume impingement effects in N-S S/K.<br>Note that many of these were not accurately predictable. | a. TM was necessary to ensure these effects did not get too big. Given bad TM (see 3.1) this severely constrained times/durations of these operations.<br>b. The magnitudes of these effects depended on time of day, putting further constraints on timing (to keep the effects within acceptable bounds).<br>c. Additional operations (momentum dumping and E-W S/K) were required to recover from these events.<br>d. Considerable O/T activity was required for attitude recovery following these events.<br>e. Extra fuel was required (for c and d above).<br>f. SHF communications was severely constrained during these events.<br>g. Excessive manpower required for planning, testing, supervision, analysis, etc. | 5/6/12 | 1. Misalignments and mass properties variations that are perfectly acceptable for normal operations may severely constrain operations requiring large-scale thruster activity.<br>2. Thruster misalignments and centre of mass variations should be:<br>a) minimized pre-launch (e.g. perhaps a split array is preferable),<br>b) analyzed as far as possible for effects pre-launch,<br>c) calibrated as accurately as possible psot-launch, and periodically throughout life.<br>3. If possible, thruster activity should occur in small, frequently repeated blocks, rather than a few very large operations.<br>4. N-S S/K using paired thrusters requires:<br>i) drastically improved yaw sensing and control,<br>ii) drastically reduced thruster mismatch,<br>iii) detailed analysis and on-orbit calibration of plume impingement (as was done on CTS/Hermes). |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
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| | | DESCRIPTION | CONSEQUENCES | | |
| 6.7 | Attitude Sensors (throughout life)<br><br>Note that, without these problems, it is possible that the S/C would not have been lost. | 1. Earth sensor prime (scan) outputs saturated for errors >2.8°.<br>2. Earth sensor secondary (cross-scan) outputs were ambiguous for errors >3.5° in one direction, and saturated for errors >3.5° in the other direction.<br>3. No earth sensor outputs for errors outside the ranges ±21° (scan direction), +12°/-5° (cross-scan direction).<br>4. Sun sensor bit-size ~1° on-axis (considerably larger off-axis).<br>5. Sun sensor outputs were anomalous and variable in the regions of head cross-over.<br>6. The rate gyros were too insensitive for use except at very high rates (e.g. in attitude acquisition).<br>7. The sun sensors occasionally gave anomalous readings, possibly related to shadowing and/or glinting. It is possible (though felt to be unlikely) that the NESA's also had occasional problems with glinting. | a. Attitude re-acquisition was extremely complex and took a long time (up to 24 hours) because of general lack of attitude information. Specifically:<br>i) Until the yaw axis was withing 21° of nominal only sun data was available, leaving the angle of rotation about the sun line unknown.<br>ii) When the earth was within view of one of the NESA's, the data was confusing and difficult to use.<br>iii) The relationship between sun-line angles and S/C angles is complex. Calculation of rates, direction and magnitude of correction torques required, etc. is very difficult and prone to error.<br>b. Performance analysis and torque environment measurement was extremely difficult due to the lack of high accuracy yaw sensing.<br>c. Control of yaw errors during major thruster firings was extremely difficult, and not totally successful (e.g. 6.6, Problem 3). | 1/5/6/ 12/13/15 | 1. Relatively coarse 4π steradian earth sensing (or its equivalent in e.g. rate integrating gyros) should be available. Normally off (to conserve power, lifetime, etc.) but automatically turned on if a major attitude anomaly occurs (see 3.5).<br>2. 4π steradian sun sensing is essential, and should be available at all times, but the whole system should be upgraded. Specifically:<br>i) Improve handling of head cross-overs.<br>ii) Eliminate anomalous outputs.<br>iii) Improve sensitivity for sun angles close to nominal (for at least some parts of the orbit).<br>3. Ground S/W should be upgraded to (on-line) integrate all available data (mass properties, dynamics, sensor outputs) to provide as accurate as possible an estimate of the angular position and rates of the satellite at all times (with or without telemetry).<br>4. The outputs of the prime NESA's should not saturate at ~15% of field of view (~50% would appear reasonable). |

Subsytem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
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| | | DESCRIPTION | CONSEQUENCES | | |
| 6.7 (cont.) | Attitude Sensors (continued) | | | | 5. Possibly high accuracy rate gyros and/or rate integrating gyros should be used.<br>6. Possibly a star tracker should be used.<br>Note that 5 and 6 are costly in money, weight, etc., but they do provide yaw information when the earth, S/C and sun are aligned while sun/earth sensor combinations do not. 3 (above) might, however, achieve the same result.<br>7. If possible, all ambiguity should be removed from sensor outputs, using 3 (above), different earth sensors, or a different sensor layout.<br>8. Upgrade analysis and testing of shadowing and reflection effects for all earth and sun sensors. |
| 6.8 | Momentum Wheel Converter (Day 277, 1978) | 1. Switch from MWC A to MWC B at NESA-A turn-on.<br>May have been caused by:<br>2. "Partial" AFP due to "partial" NESA-A anomaly (see 6.1).<br>3. Coupling between command lines.<br>4. EMI (e.g. from S/C charging). | a. Extra command required - no observable effects on attitude.<br>b. Very difficult to check exact timing, NESA outputs, etc. due to bad TM | 7 | 1. Investigate potential for partially effective automatic switching.<br>2. Upgrade isolation and EMI protection on command lines. |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
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| | | DESCRIPTION | CONSEQUENCES | | |
| 6.9 | Roll and Pitch Biases (throughout life) | 1. Bias commands were complex, difficult to use, and open to error.<br>2. Biases were on control loops, not NESA outputs.<br>3. There was a lack of planning and information on biasing in pre-launch. | a. Biases were not used (except in special tests), introducing minor pointing errors and disturbances.<br>b. If non-zero biases were used, they would have to be changed at every change in NESA ON/OFF status, and in NESA EP status. | 7 | 1. Separate bias commands; design ground S/W so that inputs are in decimal counts, or degrees.<br>2. ACE should include independent bias registers for each NESA output.<br>3. Upgrade analysis and testing to provide better information on fixed and variable biases required, and how to operationally implement them. |
| 6.10 | Roll-Yaw Control (First observed Day 045, 1976) | 1. At low external torque levels (equinox season) double dead-banding occurred because the rate-path (designed to damp nutation within the dead-band) timed out.<br>2. The rate-path time-out was calculated using mass properties significantly different from on-orbit values. | a. Excessive O/T firing (several hundred per day).<br>b. Wheel speed operating range had to be moved higher (close to unstable region).<br>c. Usable wheel speed range reduced (impacted some special operations - see 6.6, Problem 2).<br>d. Excessive time and manpower required for analysis, re-design of operations, testing, etc. | 1 | 1. Design control loops to handle wide dispersions in assumed parameter values, perhaps using on-board programmable micro-processors.<br>2. Upgrade design of rate-path (e.g. perhaps time-out was unnecessary).<br>3. Upgrade system-level analysis and control of mass properties and their effects on S/C sub-systems. |
| 6.11 | Roll-Yaw Control (throughout life)<br><br>This problem is directly related to 6.10 | 1. Damping of the nutation cone inside the dead-band was minimal, particularly at low external torque levels. | a. Excessive O/T firing (~50-100/day). | 1 | 1. Better roll-yaw controller design, including optimization of rate-path parameters. Probably requires capability for changing e.g. rate-path limiter on-board (possibly using micro-processors). |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
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| 6.12 | Wheel Speed (throughout life) | 1. Designed wheel speed operating range was not wide enough.<br>2. Torque-speed curve of driver/motor had extremely rapid fall-off ~5% above designed operating range.<br>3. Wheel speed tachometer was extremely coarse.<br>4. Wheel speed telemetry depended on telemetry bit rate (which was significantly different from nominal, and varied considerably, see 3.4).<br>Note that wheel speed changes were one of the prime indicators of RCS performance, but high accuracy was required. | a. Momentum dumping required more frequently than necessary.<br>b. Pitch loop was unstable at wheel speeds above 4400 rpm.<br>c. Severely constrained some special operations (see 6.6, Problem 2).<br>d. Considerable difficulty in calculating actual wheel speeds accurately.<br>e. The large tachometer bit-size contributed significantly to pitch rates after AFP (see 6.1). | 4/5/6/ 12/15 | 1. Drastically expand wheel speed operating range. Much of the shaping and smoothing of the torque-speed curve done in the driver/motor hardware should have been done in the control electronics (perhaps using on-board programmable micro-processors).<br>2. System-level study required of tachometer uses/requirements. Much higher resolution than 2% of nominal operating range required.<br>3. See 3.4 - Recommendations 1,2, 3 and b.<br>4. Ground S/W must be capable of simultaneously and independently averaging several subsets of parameters and displaying the results. |
| 6.13 | Pulse Count Telemetry (throughout life)<br><br>These problems were considerably magnified by the degradation/loss of telemetry (see 3.1). | 1. On-board O/T pulse counters overflowed after 31 pulses on any one thruster.<br>2. On-board pulse counters continued incrementing when O/T inhibited. | a. Tracking of pulse counts (for performance analysis, fuel use calculation, etc) was extremely difficult and time-consuming. | 1 | 1. On-board pulse counters should be sized to include the maximum expected pulses for one day.<br>2. Inhibit pulse counters when thrusters are inhibited. |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
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| | | DESCRIPTION | CONSEQUENCES | | |
| 6.14 | Pulse Rate Telemetry (throughout life)<br><br>These problems were considerably magnified by the degradation/loss of telemetry (see 3.1). | 1. O/T pulse duration telemetry was combined for positive and negative thrusters.<br>2. The telemetry was zeroed after each output.<br>3. The telemetry saturated at lower duty cycles than occurred in attitude anomalies.<br>4. Telemetry was nulled if sampling occurred while a pulse was in progress. | a. See 6.13a (above).<br>b. Considerable data was lost in attitude anomalies and re-acquisitions. | | 1. Separate pulse duration telemetry should be included for positive and negative thrusters.<br>2. Telemetry should persist after sampling, and should increment to overflow.<br>3. Counters must be sized to allow for 100% duty cycle.<br>4. Ground S/W should include cross-referencing between this TM and pulse counters to provide time of start, and duration of each pulse, with automatic recording of this data. |
| 6.15 | Wheel Speed Rundown (started after attitude anomaly and re-acquisition of Day 322, 1977). | 1. Rate of change of wheel speed increased from ~20 rpm/day to ~40 rpm/day. Returned to normal after ~3 weeks.<br>Possible causes were:<br>2. Leakage from pitch thrusters (following use in attitude re-acquisition).<br>3. Some unknown external torque.<br>This was never satisfactorily explained. | a. Considerable time and manpower required for analysis. Made very difficult by bad TM.<br>b. Minor adjustment required in M/D scheduling. | 1/4 | 1. Possibly upgrade thruster valve system.<br>2. Provide some means of detecting leaks from thrusters.<br>3. Use redundant encoders, and put temperature sensors on all thrusters. (Temperature data might have indicated anomalous catalytic decomposition in inactive thruster). |
| 6.16 | NESA Temperatures (spin phase and summer solstice). | 1. Apogee motor soak-back caused excessively high NESA temperatures for excessively long duration.<br>2. NESA's reached unexpectedly high temperatures on-orbit (summer solstice). | a. May have contributed to NESA-A anomaly (see 6.1).<br>b. Potential for damage to both NESA's (would probably have been catastrophic). | 1/7 | 1. Upgrade thermal analysis/design/testing. Specifically:<br>i) Improve conductance modelling of expended apogee motor.<br>ii) Include effects of multiple solar reflectances between angled surfaces. |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 6.17 | NESA Alignments (throughout life) | 1. Mismatch between numbers of positive and negative O/T pulses. Indicative of mis-alignment between NESA and wheel.<br>2. Variable mismatch between NESA-A scan/NESA-B cross and between NESA-B scan/NESA-A cross. Indicative of variable misalignment between NESA's.<br>3. Discrepancies between measured and predicted SHF antenna positions when boresighted at Ottawa.<br>Possible causes are:<br>4. Thermal distortions.<br>5. Basic component alignments.<br>6. Mechanical changes from test environment to on-orbit. | a. Minor increase in total number of pulses fired by one O/T.<br>b. Time and manpower required to analyze and monitor.<br>c. Confusion as to precise absolute pointing of SHF antennas.<br>d. Possible small errors in SHF antenna pointing.<br>e. Small attitude perturbations (up to 0.1°) at NESA switching. | 1/7/14 | 1. System-level study required of causes, effects, expected magnitudes, variability, measurement, and correction of ACS component misalignments. Should include a much clearer analysis of requirements/ significance of absolute pointing accuracy vs stability of pointing (short-term and long-term).<br>2. Upgrade measurement/analysis of misalignments (pre-launch), and communication of this data to operations group. |
| 6.18 | Wheel Speed Measurement (throughout last 3 years of life) | 1. Due to degradation/loss of TM, wheel speed had to be estimated by measuring nutation period using SHF signals. There was a considerable degree of uncertainty in the measurements. | a. Minor uncertainty in wheel speed. Could have become a major problem if TM completely lost.<br>b. Some uncertainty as to possible changes in mass properties. | 1/4 | 1. Detailed analysis of mass properties and dynamics should be carried out pre-launch to provide accurate relationship between nutation period and wheel speed. Must include daily, yearly and life-time variations in mass properties, differences between true and observed nutation period, etc.<br>2. Use nutation period measurement to verify on-orbit mass properties. |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 6.19 | Attitude Control Electronics (throughout life) | 1. PRC parameter set 4 could only be selected by the ACE power-on reset. (Switching ACE's had many other major effects) 2. The pitch and roll/yaw controllers were, in general, relatively inflexible. | a. Recovery from (non-AFP) attitude perturbations (e.g. following major E-W S/K) involved: i) somewhat less stable control, ii) more O/T pulses and fuel use, than would have occurred if parameter set 4 were available. b. Sufficient flexibility existed for CTS/Hermes but: i) improvement feasible, ii) longer life S/C might have problems. | 6/12/15 | 1. All logic states should be directly commandable (without power switching). 2. Use on-board programmable micro-processors. |
| 6.20 | Commanding Errors (various times throughout life) | 1. Roll/yaw controller left enabled through NESA-B sun interference. 2. Several times controllers left enabled through moon interferences, or disabled later than scheduled. Caused by: 3. Ground equipment configuration errors. 4. Operator errors. | 1. Large (~1°) attitude perturbations, but no long-term effects. 2. No significant observable effects. a. Potential for major attitude disturbances up to and including AFP trip. | 7 | 1. Upgrade ground procedures and training. 2. Possibly automate commanding at least for standard operations. 3. Build-in checks on status of all critical ground equipment, with feed-back to computer. |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
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| | | DESCRIPTION | CONSEQUENCES | | |
| 6.21 | Undesirable Operations Modes (throughout life) | 1. AFP cancel command after AFP trip would leave S/C unstable (because CWS cancelled at the same time).<br>2. During attitude re-acquisitions it was necessary to operate for long times with AFP cancelled and pitch loop enabled.<br>3. AFP had to be cancelled during NESA-B sun interferences. | a. Potentially catastrophic loss of S/C if, e.g. NESA-A anomaly occurred with AFP cancelled. | 7/13 | 1. System-level analysis required of effects of all command sequences (including non-standard).<br>2. Logic switching should be available to select parameters that can trip AFP (and other automatic switching).<br>3. Wherever possible, multiple function commands should be avoided. |
| 6.22 | Telemetry Calibration (throughout life) | 1. The engineering values of several parameters (particularly NESA cross-scan outputs) were in error in at least some parts of their ranges. | a. Considerable confusion. Time and manpower required for on-line corrections.<br>b. Potential for significant operational errors. | 1/7 | 1. Drastically upgrade measurement and recording of calibration data (pre-launch).<br>2. Ground S/W must include capability of using many different functional forms for calibration.<br>3. A direct comparison of test calibration data vs implemented calibration S/W outputs should be available to operations group. |
| 6.23 | Subcommutated Data (throughout life) | 1. TCU flags were subcommutated, but the subcommutated address stopped updating when the TCU's were off.<br>2. Several other parameters were subcommutated unnecessarily. | a. Erroneous indication when TCU's off.<br>b. Complex S/W required - occasional areas of confusion. | 1 | 1. A system-level study of TM structure required (see 3.3, Recommendation 1).<br>2. Do not sub-commutate data when spare bits are available.<br>3. Avoid sub-commutating power flags<br>4. Subcommutation mechanisms must not be powered by components whose status is part of the subcommutated data. |

Subsystem #6: Attitude Control (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 6.24 | O/T Effects on Orbit (throughout life) | 1. Because the O/T were offset 10° into yaw, they produced a non-trivial E-W effect on the S/C orbit (~0.075 cm/sec/day). This was not predicted - the radial effect of the thrusters was (as predicted) negligible. | a. Minor errors in orbit prediction, calculation of E-W S/K requirements, etc. | 3/5/12 | 1. Pre-launch analysis and post-launch calibration of the effects of all thruster firings on the orbit is required.<br>2. The off-line orbit determination prediction S/W should have the capability for including these effects. |
| 6.25 | Sun Sensor Misalignments (throughout life) | 1. Significant and variable misalignments existed between the various sun sensor heads. | a. Inaccurate yaw sensing, and inaccurate attitude sensing in re-acquisitions.<br>b. Contributed to orbit distortions due to N-S S/K (see 6.6). | | 1. Sun sensors are critically important and their pre-launch alignment must be as accurate as possible.<br>2. On-orbit calibration of the misalignments, and S/W modifications to correct for them should be carried out. |
| 6.26 | Low Thrust Engines (throughout life - first observed effects, Day 259, 1976)<br><br>This item is covered in more detail in Subsystem 8. | 1. Unexpected reduction (up to 60%) of impulse delivered by various low thrust engines.<br>2. Loss of all thrust from one offset thruster.<br>Believed to be due to:<br>3. Gas bubbles in fuel lines.<br>4. Possible valve deformations.<br>5. Possible contaminant build-up. etc. | a. Significant increase in number of operations (M/D, E-W S/K, etc.) required.<br>b. Inaccuracy in predicting effects of major operations and hence in scheduling them.<br>c. Some operations curtailed when TM bad because of unpredictability.<br>d. Significant increase in complexity of attitude re-acquisition.<br>e. Attitude perturbations (~0.2°) after one O/T failed.<br>f. Backup O/T required for normal operations.<br>g. Major attitude perturbations during N-S S/K. | 1/4/5/ 6/12/13 | 1. Design of controllers and operations must allow for significant, unpredictable and variable degradation in thrust levels.<br>2. RCS subsystem should be upgraded to minimize this problem.<br>3. Wherever possible, use of pairs of thrusters should be avoided if mismatch will create significant problems in attitude control. |

Subsystem #6: Attitude Control (continued).

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 6.26 (cont) | Low Thrust Engines (continued) | | h. Uncertainty in fuel use calculation, hence in mass properties, and in fuel margin. | | |
| 6.27 | Arcing on Solar Arrays (Day 160, 1976) (see 4.6) | 1. Large-scale attitude perturbations, believed due to expulsion of material during arcing on the pallet diode board. | a. No significant problems in attitude recovery by standard on-board systems (AFP did not trip). | 1 | |

Subsytem #7: Structures and Mechanisms

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 7.1 | Mass Properties (throughout life) | 1. Inadequate data on mass properties - measured pre-launch, predicted for post-launch, and actual post-launch values.<br>2. Inadequate data on variations in mass properties (daily, yearly and over life) - predicted and actual.<br>3. Inadequate pre- and post-launch analysis of impact of mass properties (and their uncertainties and variations) on dynamic behaviour, thruster torques, orbit changing manoeuvres, etc. | a. Uncertainty, confusion and unpredictability of effects of M/D, E-W S/K and other major S/C operations.<br>b. Performance analysis of ACS and RCS made significantly more complex.<br>c. Analysis of, and recovery from, attitude anomalies made more difficult.<br>d. Measurement of dynamic behaviour via SHF signals (for zero-TM) made much less accurate.<br>More detail on some of the problems is given in S/S 6. | 1/4/5/ 6/12/13/ 15 | 1. Drastically upgraded mass properties analysis, measurement, control and documentation required pre-launch.<br>2. Pre-launch system-level study required of:<br>i) Maximum discrepancies possible between predicted mass properties and actual.<br>ii) Expected variations in mass properties due to array motion, changes in array shape, fuel use, fuel transfer between tanks, thermal variations in structures, etc.<br>iii) Impact of discrepancies and variations on S/C dynamics and operations, and how to minimize.<br>iv) How to measure on-orbit mass properties.<br>v) Whether a method of adjusting on-orbit mass properties is required. |

Subsystem #7: Structures and Mechanisms

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 7.2 | Alignment (throughout life) | 1. Lack of easily accessible and usable alignment data on critical components. | a. Uncertainties in predicted effects of M/D, E-W S/K, etc.<br>b. Uncertainties in performance analysis of ACS/RCS.<br>c. Unexpectedly large attitude transients during major events.<br>d. Uncertainties and minor errors in SHF antenna pointing. | 1/4/5/ 6/12/13/ 15 | 1. Upgrade documentation of pre-launch alignment measurements.<br>2. Pre-launch system level study required of:<br>i) Maximum changes possible between pre-launch measurements and on-orbit misalignments.<br>ii) Expected variations in misalignments due to thermal distortion, mechanical relaxation, etc.<br>iii) Impact of misalignments on S/C performance, and how to minimize.<br>iv) How to measure and compensate for misalignments on-orbit. |
| 7.3 | Structural Damping (throughout life) | 1. Structural damping, particularly in arrays, was significantly underestimated. | a. Contributed significantly to unnecessary sluggish control loop design, particularly in pitch (see S/S 6 for more details). | | 1. Develop a system for more accurately calculating or measuring damping characteristics pre-launch.<br>2. Possibly build in mechanical dampers - very inefficient. |

Subsystem #7: Structures and Mechanisms (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 7.4 | Dynamic Behaviour (throughout life) | 1. Larger than expected attitude perturbations due to array stepping and array slewing, particularly when one array slewed alone. | a. Minor but unnecessary attitude perturbations. Possible impact on SHF communications. b. Time and manpower for analysis. c. Introduced same constraints on non-standard operations. | 1/11 | 1. Reduce array step-size in auto-track mode. 2. Upgrade pre-launch analysis and simulation of array stepping and slewing and their impact on dynamics and control in all axes (particularly coupling into roll/yaw). Include non-standard array operations. |
| 7.5 | Grounding (throughout life) | 1. Grounding of some structural elements (particularly the solar array) was inadequate. | a. Arc on pallet diode board caused significant attitude perturbations, and the loss of ~15% of experiments array power. b. Several other possible EMI-caused phenomena (see S/S 11) | | 1. Upgrade grounding and S/C charging/EMI protection - see S/S 11. |
| 7.6 | Jettisonable Body Solar Arrays (attitude acquisition) | 1. Waste of H/W and power when JBSA's jettisoned. | a. Potential weight saving. b. Potential increase in power available, particularly in non-standard attitudes. c. Potentially simpler thermal design. | 1/13 | 1. Design structures and mechanisms to eliminate the need to jettison H/W and solar cells (if possible). |
| 7.7 | Array Orientation Control (throughout life) Note that without these problems, the S/C probably would not have been lost (see consequence g) | 1. Very complex multiply-cross-linked array orientation controller/driver/motor system. Potential for: i) Permanent fast slew ii) Prime and redundant drivers on together. 2. Primary control mode used clock stepping. | a. Complex command sequence required; minor errors occurred (wrong doublet step size, etc.). Potential for catastropic errors. b. Complex TM requirements; insufficient space left ambiguities in flagging of operational modes. | 1/11/13 | 1. System should be designed and tested with sun-track mode as prime. 2. Detailed study of control/drive modes, cross-strapping requirements, etc. Emphasis should be on reliability (including potential for errors), but simplicity must also be a major design goal (e.g. eliminate interlacing capability). |

Subsystem #7: Structures and Mechanisms (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 7.7 (cont) | Array Orientation Control (continued) | 3. Array sun sensors had inadequate fields of view<br>4. Auto-track dead-band was too large.<br>5. Auto-track mode (particularly sun-sensors) was not qualified for permanent use.<br>6. Unsophisticated auto-track controllers would reverse slew unnecessarily under the appropriate dynamic conditions (e.g. at first sun re-acquisition after loss of tracking due to pitch rate > slew capability).<br>7. Uncertainty in operating mode at turn-on.<br>8. In clock mode, probability of achieving interlaced stepping was 50%. Fortunately, this had no impact on S/C behaviour/performance. | c. Non-nominal clock frequencies required daily manual updates of array orientation when in clock mode. This was a complex operation, and required good telemetry.<br>d. Clock mode inadequate after attitude anomalies.<br>e. Effects of stepping on pitch were unnecessarily large in auto-track.<br>f. Use of auto-track mode was risky, and wasted scarce battery power under some conditions.<br>g. Loss of array sun-track for varying durations was highly likely after attitude anomalies, e.g.<br>i) A half-cone angle of ~40° in roll-yaw, and a pitch rate of ~12°/minute caused permanent loss of array tracking on Day 330, 1979.<br>ii) Permanent loss of sun tracking could have resulted from a 10° precession (in the appropriate direction) at solstice. | | 3. The array sun sensors should have drastically expanded fields of view (2π Steradians appears reasonable).<br>4. In auto-track, step size should be significantly reduced. Perhaps, in standard mode, some form of essentially continuous drive is feasible.<br>5. Controller design must take into account non-standard situations (particularly attitude anomalies) and should be considerably more sophisticated.<br>6. Power-on reset should have been used to put controller and switching in safe, known state.<br>7. A higher fast slew capability would have been helpful after attitude anomalies, but the power requirements might have been too high.<br>8. Detailed study required of telemetry to ensure no ambiguities. |

Subsystem #7: Structures and Mechanisms (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 7.8 | Array Angle Encoders (throughout life) | 1. Encoder range was 30°.<br>2. Two bits lost from Encoder outputs (problems observed in this area pre-launch).<br>3. Occasional apparent steps backwards (not real).<br>4. Used 8 flags for TM. | a. Considerable ambiguity and confusion re array orientation, particularly after attitude anomalies. | 1/11/13 | 1. Encoders must cover full 360° positions unambiguously. It does not appear that 0.125° resolution was necessary. If it is, increase the word size (to 13 bits) rather than decreasing the range. Possibly a coarse sensor and a vernier would be best.<br>2. Do <u>not</u> fly components that fail during pre-launch testing.<br>3. Upgrade design, manufacture and testing of encoders.<br>4. Use a digital word rather than multiple flags. |
| 7.9 | Array Deflection Sensors (throughout life) | 1. Deflection sensor data did not correlate with other data due to mixed up sensors/calibrations. | a. No significant consequences except for ACS experimenters. | 1/11 | 1. Upgrade identification and control of similar but non-identical components. |
| 7.10 | SAMA Power Switching (Day 273, 1976 Day 079, 1977) | 1. Uncertain secondary module configuration when SPC turned on.<br>2. Logic switches controlling power supplied by SAMA 27.5V controlled by power from SAMA secondary module. | a. Complex command sequences required, with potential for errors.<br>b. Potential for partially on circuits, and damage to solid state switches when secondary module off with MHC power supply on. | | 1. Wherever possible, power-on resets should be applied to all components downstream of a power supply before power is applied to them.<br>2. Do not use logic switches where power controlling the switch can be off at the same time as power through the switch is on. Either:<br>i) Use latching relays or<br>ii) Use a common power supply.<br>3. Turning off the SAMA secondary power (by command or trip) should have turned off the 27.5V power supply. |

Subsystem #7: Structures and Mechanisms (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 7.10 (cont.) | SAMA Power Switching (continued) | | | | 4. Automate (on-board or in ground S/W) switching sequence for SAMA power supplies. |
| 7.11 | Potential Uses of Arrays | (Not Implemented on CTS/Hermes) | | 1/8/9 | 1. Possibly use array orientations to manipulate solar torques, thus reducing number of thruster firings, fuel used, etc.<br>2. Possibly use array orientations in conjunction with a shunt regulated system, to control thermal dissipation in shunt, battery charging, etc.<br>Note that:<br>i) These appear to be mutually exclusive<br>ii) Major stystem-level study is required before attempting to implement either of them. |

Subsystem #8: Reaction Control

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 8.1 | Low Thrust Engines (throughout life - first major drop in performance of P1 observed on Day 259, 1976)<br><br>Note that these problems contributed to the loss of the S/C - see consequence ℓ. | 1. Many of the LTE's, particularly those that were used a lot, exhibited extremely variable under-performance (delivered impulse as low as 40% of predicted for a pulse train; possibly as low as 0% for individual pulses).<br>The most probable cause was:<br>2. Gas bubbles in the lines (see 8.3 below).<br>Other possible causes include:<br>3. Degradation of valves (e.g. valve seat swelling as was observed in pre-launch test) as a result of excessive temperatures and/or material degradation.<br>4. Two phase flow in the lines and/or thrust chambers due to excessive temperatures (perhaps soak-back from the thruster itself and/or flashback).<br>5. Line blockage by contaminants due to e.g. diaphragm degradation/ partial break-up.<br>6. Catalyst bed poisoning, washout, cracking or other deterioration.<br>7. Freezing of hydrazine in the lines/ chambers. | a. Extreme unpredictability of results of major operations (momentum dumping, E-W stationkeeping, N-S stationkeeping, etc.).<br>b. Severe constraints on major operations (particularly when TM was bad).<br>c. Very complicated scheduling of major operations (particularly when TM status was unpredictable).<br>d. Significant increase in number and complexity of major events.<br>e. Significant increase in number of thruster firings required; possibly increased fuel usage.<br>f. Large-scale uncertainty in fuel usage/margin as calculated from performance data.<br>g. Large attitude perturbations during N-S S/K due to large mismatch between thrusters.<br>h. During N-S S/K, yaw errors caused significant tangential thrusting, leading to large-scale orbit deformation. This required extra E-W S/K and fuel use.<br>i. Unexpected, unpredictable small attitude perturbations during all major events.<br>j. Some constraints on SHF operations, particularly during N-S S/K. | 4/5/6/ 12/13/15 | 1. Since these problems appear to be generic to hydrazine systems (ref: OTS, ATS, etc.), perhaps some other thrust/torque system should be used. Some potential candidates are:<br>i) Ion engines<br>ii) Magnetic torques<br>iii) Various bi-propellent systems<br>iv) Various cold-gas systems.<br>2. A system-level study is required in the conceptual design phase to select the optimum torquing system, and these problems must be taken into account if hydrazine systems are to be considered.<br>3. If a hydrazine system is used, the impacts on the S/C include:<br>i) Extra fuel must be carried (to allow for extra thruster use to compensate for under-performance).<br>ii) Attitude Control Systems (on-board and in ground S/W) must allow for significant, unpredictable and variable degradation in thrust levels.<br>iii) Use of pairs of thrusters where mismatch will cause attitude problems should be avoided if possible. If such use is unavoidable |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 8.1 (cont) | Low Thrust Engines (continued) | | k. Excessive time and manpower required for analysis of problems, redefinition of procedures, special S/W (e.g. for N-S S/K), scheduling, specialist supervision of operations, etc.<br>ℓ. Increased difficulty and uncertainty in:<br>i) Reacquiring after attitude anomalies.<br>ii) Analyzing effects of attitude anomalies.<br>iii) Predicting effects of attitude anomalies. | | 3. iii) (continued) (appears likely for N-S S/K), control systems must be capable of handling large-scale mismatch (possibly up to 100%).<br>4. It is possible that these problems could have been avoided by significantly upgrading the RCS design. Specifically:<br>i) Drastically improve thermal design to reduce extremes (hot and cold) and to minimize temperature cycling.<br>ii) Upgrade valve materials and design.<br>iii) Upgrade diaphragm to reduce permeability and degradation.<br>iv) Upgrade catalyst bed materials/structure.<br>5. More complete mapping of thruster firing is required in test, particularly over intermediate ranges of temperature and pressure. |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 8.2 | Offset Thrusters (Day 270, 1979) | 1. Zero thrust from one O/T (01). Possible causes included:<br>2. Valve sealed shut due to distortion and/or material degradation, possibly as a result of excessive temperatures.<br>3. Fuel line or filter blockage by contaminants (e.g. from the diaphragm).<br>4. Catalyst bed poisoning, washout or cracking.<br>5. Loss of the chamber heater (unlikely because heater current drain did not change, but possibly because no chamber temperature available).<br>6. Freezing of hydrazine in line and/or chamber.<br>It is possible that this failure is directly related to 8.1. Certainly 01 exhibited signs of major degradation before failure. It was very difficult to determine the performance levels of the O/T in general due to the complex dynamics/control involved, and due to lack of good mass properties data. | a. Relatively large-scale roll-yaw attitude errors (of up to 0.25°) until switch to redundant thrusters.<br>b. Backup O/T 03 and 04 had to be used. Potential catastrophe if 03 failed.<br>c. Heater for redundant thrusters required more power (impacted eclipse load shedding), and increased the temperatures in all four rocket engine modules (REMS).<br>d. Excessive time and manpower required to analyze problem, test thrusters, redefine procedures, and monitor for thermal problems when redundant thrusters in use.<br>e. Uncertainties introduced in using unfamiliar thrusters (e.g. in size on cone expected after attitude anomaly). | 1 | 1. See Recommendations of 8.1 in general.<br>2. Develop (pre-launch) detailed methods of measuring O/T performance throughout life.<br>3. Upgrade monitoring and analysis of O/T performance on-orbit.<br>4. Design back-up thrusters (including heaters) to have essentially the same impact on the system as the prime thrusters (particularly thermal and power).<br>5. Possibly use a surface tension system (if contamination from diaphragm). Note that this would probably worsen the problems of 8.1 and 8.3. |
| 8.3 | Gas Generation (throughout life)<br><br>Note that, without these problems, the S/C would not have been lost (see Consequence a). | 1. Significant quantities of gas were present in the fuel tanks and lines, in both dissolved and free (bubble) form.<br>Possible sources:<br>2. Permeation of the pressurant (nitrogen) across the diaphragm.<br>3. Auto-decomposition of hydrazine in the lines, with the rate drastically increased by high temperatures. | a. The O/T generated significant impulse when fired with the main tank latch valves closed. This caused large cone/precession effects after attitude anomalies (see 6.1).<br>b. Bubbles, two phase flow, etc. caused significant degradation in thruster performance (see 8.2). | 1/4/5/ 6/8/12/ 13/15 | 1. See Recommendations of 8.1 in general.<br>2. Drastically upgrade pre-launch analysis of auto-decomposition rate of hydrazine, and select temperature ranges to reduce it to an acceptable level.<br>3. Drastically upgrade the thermal design and operations to meet the requirements of 2 (above). |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 8.3 (cont.) | Gas Generation (continued) | 4. Vapourization of hydrazine, again significantly impacted by temperature.<br>Note that dissolved gas had minimial impact. Creation of gas bubbles is significantly increased by:<br>5. Daily (and shorter term) temperature cycling.<br>6. Decrease in pressure.<br>7. Existance of formation points (e.g. sharp corners, fine filter elements, etc.).<br>etc. | c. Unexpected variations in tank pressure occurred.<br>d. Relationship between tank pressure and remaining fuel was very uncertain.<br>e. ACS/RCS performance was unpredictable because of pressure uncertainties. | | 4. Automatic failure protection trip must ensure that no thrusters can be fired.<br>5. Possibly modify the mechanical design of fuel flow paths to eliminate bubble formation points.<br>6. Possibly change to a constant pressure fuel supply system. |
| 8.4 | Fuel Tank Pressure (throughout life) | 1. West fuel tank pressure was not available. Lost at initial opening of main tank latch valves in spin phase. Valves chattered under high surge flow; resulting pressure spikes permanently damaged the pressure transducer.<br>2. East tank pressure sensor was highly non-linear, insufficiently sensitive, and suspect in performance and calibration. In pre-launch testing, this transducer failed, and was "band-aided" for flight.<br>Note that the two failures may have been related. | a. Unexpected changes in telemetered tank pressure - may have been due to gas in the system (see 8.3) rather than pressure transducer.<br>b. Large uncertainties in RCS and ACS performance analysis and prediction.<br>c. Large uncertainties in calculation of remaining fuel.<br>d. Excessive time and manpower required for analysis of problems.<br>e. Potential for loss of all pressure data (for fuel calculation, performance prediction/analysis, etc.) if East tank pressure sensor failed. | 1/4/5/ 6/12/13/ 15 | 1. Do not fly components that fail during pre-launch testing. If it is essential to refurbish and fly such components, time and resources must be available so great care can be taken to ensure that the causes of the failure are completely understood and corrected. Much better to have fully qualified flight spares available.<br>2. If a component fails during test, additional, more rigorous testing should be applied to all similar units.<br>3. Testing of a pressurized system must include operation of all valves under conditions of maximum pressure differential.<br>4. Pressure transducers can and must be protected against pressure spikes. |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 8.4 (cont) | Fuel Tank Pressure (continued) | | | | 5. Some means (other than the predicted blow-down curve) must be used to calculate remaining fuel. Possibly a system for detecting diaphragm position/ shape is feasible. |
| 8.5 | Fuel Tank Temperature (throughout life) | 1. West fuel tank temperature was not available. The power supply burned out as a result of a short caused by the damaged pressure transducer (see 8.4, Problem 1).<br>2. Fuel tank temperature sensors did not indicate fuel/pressurant temperature. | a. Some uncertainties in calculation of remaining fuel.<br>b. Potential for loss of blow-down system of calculating fuel if East tank temperature sensor had failed. | 1 | 1. Locate tank temperature sensors inside the tank, preferably immersed in the pressurant, if feasible.<br>2. See 8.4, particularly Recommendation 5. |
| 8.6 | Thruster Chamber Temperatures (throughout life)<br><br>Note that these problems contributed to the S/C loss (see Consequence c). | 1. All thrusters required preheating before firing.<br>2. The chamber temperatures of all four O/T, and of the East and West thrusters were unavailable, as they had the same power supply as the West fuel tank temperature (see 8.5, Problem 1).<br>3. No chamber temperature sensors were flown on the backup roll, pitch and yaw thrusters.<br>4. The chamber temperatures on the prime roll, pitch and yaw thrusters were only available on Encoder A. | a. Uncertainties in temperatures of some thrusters when fired. Potential damage if too cold. Could have contributed to 8.1 and 8.2.<br>b. Uncertainties in RCS performance analysis and prediction.<br>c. Long preheat times required on all thrusters. Significantly greater times required for those with no chamber temperature TM, and when TM was lost.<br>d. Had to switch to Encoder A for virtually all operations involving thruster firing.<br>e. Excessive power and time required during re-acquisition. | 4/5/6/ 12/13/15 | 1. All thrusters should carry chamber temperature sensors.<br>2. See 8.4, Recommendations 1,2,3,4<br>3. Use fully redundant Encoders (see 3.3).<br>4. If feasible, systems should be designed so thrusters can be fired cold. This is particularly important for time and power saving in attitude re-acquisition.<br>5. Upgrade accuracy/reliability of predicted required preheat times (to minimize time required when temperature data is not available). |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 8.7 | Thermal Control of Lines, Valves, Tanks, etc. (throughout life)<br><br>Note that it is highly likely that these problems contributed significantly to the problems discussed in 8.1, 8.2 and 8.3. | 1. Insufficient and improperly placed temperature sensors (e.g. no sensors on critical elements in the East REM).<br>2. Heaters were not located properly (e.g. heater used for North and South REM's put too much heat into main S/C body rather than REM).<br>3. Heaters were very badly grouped (e.g. Heater G had elements in all four REM's).<br>4. RCS operations (thermal control, and thruster preheat and firing) had an unexpectedly large impact on the rest of the S/C. Similarly S/C operations (especially TEP operations) had a significant impact on RCS thermal behaviour.<br>5. Many heater commands performed multiple functions.<br>6. Most of the critical temperature TM, and one critical heater flag, were only available on Encoder A.<br>7. Operational temperature limits were originally chosen as expected values, rather than allowable extremes. | a. Large uncertainties in thermal control.<br>b. Over one day, the East REM was coldest when the West REM was hottest (and vice versa). Despite this, it was not possible to heat the East REM without also heating the West REM. Similarly (over a year) for the North and South REM's.<br>c. Excessive heater cycling (up to 10 per day on one heater) required, with attendant risks of heater failure.<br>d. Extremely complex and frequent heater operations, and complex S/W required, with resultant errors (some severe, potentially catastrophic).<br>e. Operational temperature limits were frequently exceeded, even though they were adjusted outwards many times (to reduce heater cycling).<br>f. Components subjected to unnecessarily extreme high and low temperatures, and unnecessary cycling between them. | 1/8 | 1. RCS thermal control <u>must</u> be integrated with S/C thermal control system.<br>2. Drastically upgraded analysis, design and test of RCS thermal control required, with much more attention paid to the simplicity and reliability of the required on-orbit operations.<br>3. Ensure that the temperatures of all critical components are available either directly from sensors or extrapolated (in ground S/W) from sensor data, using test data.<br>4. Heaters must be broken up into small, separately commandable elements (perhaps using value commands to reduce the number of command channels required). Specifically, each REM <u>must</u> have its own, independent heater.<br>5. System-level study required of heater and temperature sensor locations, heater sizes, required operations, etc.<br>6. Use thermostatically controlled heaters (but only after 5).<br>7. Use fully redundant Encoders (see 3.3). |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 8.7 (cont) | Thermal Control of Lines, Valves, Tanks, etc. (continued) | | g. Heater operations, temperature limits, S/W, etc. had to be frequently updated, with resulting confusion.<br>h. Much of the critical data was unavailable most of the time. Many Encoder cycles required to obtain minimal data to check operations.<br>i. Heaters required excessive power (because more elements were being heated than was necessary). This added to problems in eclipse and attitude re-acquisitions.<br>j. The whole system was critically dependent on TM. Operations with no/bad TM required a drastic decrease in heater cycling (leaving a heater in the incorrect state for more than an hour could cause catastrophic failure). This in turn caused the qualification temperature limits to be exceeded.<br>k. Excessive time required for data gathering and analysis, rewriting and testing of procedures, etc. | | 8. Use acceptable temperatures as operational limits (rather than predicted).<br>9. Drastically upgrade off-line data processing capability. |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 8.8 | Heater Failure Detection (throughout life) | 1. RCS Input Current varied from 0 to 0.02 A low after Heater G was turned on permanently.<br>Possibly due to:<br>2. Intermittent failure of an element of Heater G.<br>3. Temperature sensor/TM Encoder variations (e.g. with temperature). | a. Potential damage in area of failed element.<br>b. Excessive time and manpower required for data gathering and analysis. | 1/8 | 1. Note that this single parameter could have been extremely useful in monitoring for failures in a large number of components (particularly heaters). To be effective, however:<br>i) Pre-launch testing must be more complete (e.g. to cover the effects of temperature variations).<br>ii) The sensitivity of the sensor must be increased so that the loss of any one element causes an easily observable change.<br>iii) Complete detailed data must be available to the operations group. |
| 8.9 | Offset Thrusters and Chamber Heater Commands (throughout life) | 1. Single value command used for O/T Arm/Inhibit, and all LTE chamber heaters.<br>2. Chamber heaters were not separately commandable. | a. Confusion, and occasional errors in operations (minor but potentially catastrophic).<br>b. Excessive power use and increased temperatures when more than the required thrusters had to be heated. | 1/7 | 1. Separate commands for O/T from those for other chamber heaters.<br>2. Provide separate command capability for each chamber heater.<br>3. Automate (on-board or in ground S/W) check that appropriate heaters are on before thrusters (particularly O/T) are fired. Must be over-rideable for non-standard situations.<br>4. Operator inputs should be related to effects of commands where feasible. |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 8.10 | Pulse Count Telemetry (throughout life) | 1. RCS PC TM periodically stepped backwards, due to sampling when the analogue sensor was in the process of overflowing.<br>2. Overflow occurred at 16 pulses. | a. Confusion and errors in data interpretation.<br>b. Complicated ground S/W required.<br>c. Data lost whenever TM noisy, or when short-term TM losses occurred (e.g. in attitude re-acquisition). | 1/13 | 1. This was an extremely useful parameter when available. Significant improvements that should be made are:<br>i) use a digital counter;<br>ii) size counter to include the expected maximum number of pulses for one day. |
| 8.11 | Thruster Leakage (after attitude anomalies on Day 322, 1977, Day 120, 1979, Day 237, 1979) | 1. Daily change in wheel speed increased from ~20 rpm to ~40 rpm.<br>2. Pitch rate showed significant variations during quiescent periods between occurrence of attitude anomalies and start of re-acquisition (did not happen after all anomalies).<br>3. "Pitch glitches" may have been related to these problems.<br>Possibly due to:<br>4. Leaking pitch thruster, with partial or total decomposition of hydrazine, depending on thermal environment. Leak may have been caused by valve deformation, contaminants, etc. | a. Potential for loss of several thrusters (if long-term leakage required closing of latch valves).<br>b. Loss of fuel (minor, potentially major).<br>c. Considerable time and manpower required for analysis.<br>d. Significant additional problems in some re-acquisitions.<br>e. Uncertainties in fuel margin. | 1/13 | 1. Possibly upgrade the thruster valve system.<br>2. Provide some means of detecting leaks from thrusters directly.<br>3. Provide accessible TM on all thruster chamber temperatures (see 8.6) - might have indicated anomalous firings.<br>4. Upgrade monitoring and analysis of data. |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 8.12 | RCS Power Switching (Day 273, 1976 Day 074, 1977 Day 278, 1977) | 1. Uncertain secondary module configuration when SPC turned on.<br>2. Logic switches controlling power supplied by RCS 27.5V (MHC) controlled by power from RCS secondary module.<br>3. Heater E turned on spontaneously - cause unknown, but possibly related to other SPC/secondary module problems (see Consequence c), S/C charging, etc. | a. Complex command sequences required with potential for errors.<br>b. Heaters E, F and G turned partially on when secondary module off.<br>c. Potential damage to solid state switches. | 1 | 1. Whenever possible, power-on resets should be applied to all components downstream of a power supply before power is applied to them.<br>2. Do not use logic switches where power controlling the switch can be off at the same time as power through the switch in on. Either:<br>i) use latching relays, or<br>ii) use a common power supply.<br>3. Turning of RCS secondary power supply (by command or trip) should have turned off the RCS 27.5V power supply.<br>4. Automate (on-board or in ground S/W) switching sequence for RCS power supplies.<br>5. Upgrade EMI protection (see S/S 11). |
| 8.13 | Performance Prediction (throughout life) | 1. Prediction of impulse, fuel usage, etc. from various thrusting sequences was difficult, and inaccurate, particularly for large-scale manoeuvres (e.g. N-S S/K) not included in pre-launch planning. | a. Uncertainties in predicting effects of major operations.<br>b. Excessive time and manpower required, particularly for data extrapolation. | 6/12 | 1. Upgrade testing and (more particularly) recording of pre-launch performance test data. A format must be used that permits accurate interpolation and extrapolation (e.g. provide functions relating performance parameters to telemetered parameters). |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 8.14 | Thruster Impulse Bits (throughout life) | 1. O/T minimum impulse bits were perhaps too high. | a. Possibly more pulses than necessary, particularly when external torques low.<br>b. Possible fuel savings. | 1 | 1. This was of considerable concern during design, but no on-orbit problems resulted (total pulse counts over 4 years were less than 2-year qualification).<br>2. If feasible, a reduced O/T torque-bit would provide improved performance, and might simplify ACS design. |
| 8.15 | Mass Properties of Fuel System (throughout life) | 1. Changes in mass properties of fuel system (and hence in S/C) with fuel use undefined.<br>2. Occurrence and effects of fuel transfer between tanks not defined. | a. Inadequate definition of S/C mass properties (see 7.1 for further consequences).<br>b. Excessive time and manpower for analysis. | 1/4/5/ 6/12/13/ 15 | 1. Drastically upgrade pre-launch analysis of mass properties of fuel system and their variations.<br>2. Better communication of this data to S/C systems group.<br>3. Some means should be provided of calculating the amount of fuel remaining in each tank (see 8.4, Recommendation 5). |
| 8.16 | Fuel Tank System (late in life) | 1. Due to loss of S/C before hydrazine exhausted, no data obtained on RCS performance at very low pressure/ remaining fuel.<br>2. Protection against running out of fuel would have required introducing asymmetry in fuel storage. | a. Loss of data useful for future S/C design.<br>b. Potential problems in performance due to asymmetric mass properties. | 1 | 1. Possibly use a 4 tank system with one pair in normal use (as on CTS), and the other pair used:<br>i) after exhaustion of first pair,<br>ii) to provide a known fuel margin,<br>iii) as back-up in case the prime fuel supply system fails. |

Subsystem #8: Reaction Control (continued)

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 8.17 | O/T Effects On Orbit (throughout life) | 1. O/T firing caused unexpected significant effects on the orbit due to the tangential thrust component (radial thrust component had, as predicted, negligible effect). | a. Minor errors in orbit prediction, calculation of E-W S/K requirements, etc. | 3/5/12 | 1. Pre-launch analysis and post-launch calibration of all effects of all thruster firings on the orbit required. |
| 8.18 | Plume Impingement (during N-S S/K) | 1. Significant torques (particularly in pitch) due to plume impingement on the arrays during N-S S/K. | a. Minor attitude perturbations and wheel speed effects.<br>b. Considerable time and manpower required for analysis and test. | 6 | 1. This effect was quite accurately predicted on CTS. Detailed analysis and on-orbit calibration is required before N-S S/K is implemented. |
| 8.19 | Non-Standard Commands (after each attitude anomaly) | 1. Long on-time commands (~2-3 seconds vs standard 50 msec) used to open main tank latch valves (because of spin phase failure - see 8.4). | a. Minor commanding complexity.<br>b. Potential for major error. | 13 | 1. See 8.4.<br>2. Automate constraints on commands in ground S/W. |
| 8.20 | Performance Measurement (throughout life) | 1. Measurement of thruster performance was uncertain and inadequate, particularly for O/T. Especially significant in light of problems of 8.1. | a. Uncertainties in performance precitions, fuel use calculations, mass properties, etc. | 1/4/5/6/12/13/15 | 1. System-level study required pre-launch of requirements for, and methods of, reassuring thruster performance. Recognition of significance of accurate measurement of wheel speeds, orbit changes, etc. for this purpose. |

Subsystem #9: Apogee Motor

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 9.1 | Heat Soak Back (spin phase) | 1. NESA's and batteries reached very high temperatures (see S/S 4, 6 and 10). | a. See S/S 4, 6 and 10. | | 1. Upgrade thermal analysis and design - specifically the conductance modelling of the expended apogee motor. |
| 9.2 | Mass Properties (throughout life) | 1. Uncertainties in mass properties of expended apogee motor. | a. See 7.1 | | 1. Upgrade analysis and testing of expected mass properties of expended apogee motor.<br>2. See 7.1, Recommendation 2. |

Subsystem #10: Thermal

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 10.1 | Whole Subsystem (throughout life)<br><br>This item provides a S/S overview and covers many of the points included in more detail later. | 1. Thermal operations in general were excessively complex.<br>2. Many component temperatures exceeded design limits (hot and/or cold).<br>3. Thermal control depended totally on usable TM. The degradation/loss of TM (see 3.1) forced changes in thermal operations that, in some cases, caused component temperatures to exceed qualification limits.<br>4. Many components experienced unexpectedly large temperature variations (over a day, a year, and life). | a. Complicated procedures, command sequences, etc. were confusing, and caused many errors, some significant, potentially catastrophic.<br>b. Many components were, to a greater or lesser degree, subjected to thermal stress.<br>c. The degradation and/or failure of some components was related to thermal environment. | 1/8 | 1. Drastically upgrade thermal design, simulation and testing.<br>2. All aspects of thermal environment and control must be integrated. Specifically, RCS thermal control must be integrated with the rest of the thermal S/S.<br>3. System-level design must include better recognition/ appreciation of:<br>i) The large (E-W and N-S) thermal gradients, and the large (daily and yearly) component temperature variations, experienced by 3-axis stabilized S/C (as opposed to spinners).<br>ii) The variability of S/C operational modes.<br>iii) The operational requirements implied by the thermal design, with emphasis on simplicity and reliability of operations, procedures, S/W, etc.<br>Tests and simulations must cover these areas more completely and accurately, and must ensure no negative impacts on the S/C.<br>4. It appears very unlikely that purely passive thermal control (as was originally visualized for CTS/Hermes) is feasible. |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 10.1 (cont.) | Whole Subsystem (continued) | | | | 4. (continued) Besides heaters, other active elements that must be considered are heat pipes and louvres.<br>5. On-board automatic control (e.g. thermostatically controlled heaters) would significantly reduce problems in ground operations and increase reliability, particularly in non-standard situations. |
| 10.2 | Heater Commands (throughout life) | 1. Complex interlinked heater commands (e.g. Heater 4 had to be turned on whenever Heater 2 was turned on). | a. Confusing and complex heater command sequence required occasional errors, some significant, potentially catastrophic.<br>b. Large numbers of unnecessary heater cycles, with risk of failure. | 8 | 1. All heaters must be separately commandable on and off (perhaps use value commands to reduce the number of command channels required).<br>2. Use thermostatically controlled heaters, with changeable limits (perhaps using programmable on-board microprocessors). Note that ground override of any automatic switching must be provided.<br>3. Upgrade ground S/W used to control heaters. Possibly include automatic commanding . |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 10.3 | Heater Operations (throughout life) | 1. Heater locations and thermal coupling were not optimal (e.g. Heater 3, required to heat N+S REM's, put too much heat into the rest of the S/C).<br>2. Heaters were very badly grouped (e.g. Heater 3 had elements on both the N and S panels).<br>3. Heater operations were critically dependant on TM, and had to be significantly compromised when TM Tx degraded. | a. In many cases, in order to maintain high enough temperatures in one area of the S/C, it was necessary to overheat another area.<br>b. Significant changes in operations with time of year required.<br>c. Confusing, complex and continuously changing operations, S/W and procedures. Occasional errors, some significant, potentially catastrophic.<br>d. Excessive number of heater cycles required (with associated risk of failure).<br>e. Excessive time and manpower required for data gathering and analysis, S/W and procedure updates, operations testing, etc.<br>f. Some components were subjected to unnecessarily high and low temperatures, and to unnecessarly cycling between them.<br>g. Excessive power used, with significant negative impact in eclipse and re-acquisition.<br>h. High risk of thermal problems when TM bad or unavailable (due to Tx problems or attitude anomalies). | 8 | 1. System-level design must include:<br>i) Incorporation of heaters much earlier in the design phase (and possibly other active elements as well).<br>ii) Better distribution of heat throughout the S/C, perhaps using heat pipes (or see 4 below).<br>2. Heaters must be broken up into small, separately commandable elements.<br>3. Heater locations must be chosen such that areas that experience significantly different thermal environments do not share the same heater.<br>4. Perhaps a modular approach, with each module thermally isolated from the others and with its own heater, should be used.<br>5. The number of heater cycles required must be analysed, and the impact on reliability taken into account.<br>6. Use thermostatically controlled heaters (but include 5 above). |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 10.4 | Heater Telemetry (throughout life) | 1. Heater flags were not all included on both Encoders. | a. Complex S/W required with occasional errors.<br>b. Heaters were sometimes left on when they should have been off, with significant overheating of some components. | 8 | 1. Use fully redundant Encoders (see 3.3).<br>2. Upgrade ground S/W (e.g. a fully implemented switching model). |
| 10.5 | Temperature Sensors (throughout life) | 1. Temperature sensors were not positioned properly relative to heaters.<br>2. Lack of sensors on some critical components (e.g. the East REM).<br>3. Insufficient sensors in general (particularly given the large thermal gradients).<br>4. Thermal coupling of some sensors to the S/C was inadequate and/or inappropriate.<br>5. Array temperature sensors were mounted under non-representative solar cells. | a. Inadequate indications of correct functioning of heaters.<br>b. Uncertain thermal control, with possible damage to critical components.<br>c. Inadequate data for analysis; particularly significant when planning zero-TM operations, and for non-standard situations.<br>d. Inadequate data for RCS operations and analysis (see S/S 8).<br>e. Inaccurate data on array thermal behaviour, power characteristic measurements, etc. | 8 | 1. System-level study required of number and location of sensors. Must include:<br>i) How to determine whether each heater is operating correctly.<br>ii) How to adequately control each heater.<br>iii) What data is necessary to adequately determine the S/C thermal status (particularly components subject to temperature extremes and components sensitive to thermal variations).<br>iv) What data is necessary to predict S/C thermal status (e.g. in non-standard attitudes). |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 10.6 | Temperature Telemetry (throughout life) | 1. Many critical temperatures were only available on one Encoder.<br>2. Several important RCS temperatures lost in spin phase (see S/S 8).<br>3. Array temperatures were lost when SATE was lost. | a. Many Encoder cycles required to obtain minimal data to check operations.<br>b. Some risk of subjecting components to excessive temperatures.<br>c. Complex S/W and operations instructions required.<br>d. Lack of data for analysis and planning (particularly for zero-TM). | 1/8 | 1. Use fully redundant Encoders (see 3.3) and subcommutate temperature data.<br>2. See 8.5<br>3. Upgrade analysis of criticality of temperature TM for heater control and for analysis/prediction of S/C thermal behaviour. Investigate reliability, and possible requirements for redundant TM. |
| 10.7 | Prediction of Thermal Behaviour (throughoutlife) | 1. Inadequate data on expected thermal behaviour available to operations group, both for pre-launch planning and during on-orbit operations.<br>2. Inadequate data on the uncertainties in predicted behaviour.<br>3. Inadequate data on behaviour in non-standard situations. | a. Uncertainties in operations. Note that what were predicted to be "impossible worst cases" in general occurred on the real on-orbit S/C.<br>b. Temperature limits used to control heaters and to indicate potential problems had to be changed frequently, resulting in confusion, errors, excessive use of time and manpower, etc.<br>c. Excessive dependance on TM.<br>d. Predictions based on previous performance were inadequate due to surface degradations, operational changes, etc.<br>e. Large uncertainties in planning changes in operations (e.g. for zero-TM). | 1/8 | 1. Upgrade testing, simulation and analysis to provide expected behaviour (as opposed to meeting spec.). Must include effects of:<br>i) Heater operations.<br>ii) Other S/C operations (e.g. TEP).<br>iii) Effects of degradations in materials, heaters, power supply, etc. over life.<br>Improve communication of this data to operations group.<br>2. Limits should be used <u>only</u> to:<br>i) Provide triggers for operational activities (e.g. heater switching).<br>ii) Warn of significant problems requiring immediate responses.<br>3. Upgrade off-line data processing and analysis to provide:<br>i) Advance warning of potential problems. |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 10.7 (cont) | Prediction of Thermal Behaviour (continued) | | f. Large uncertainties in the thermal status after attitude anomalies and/or UVS trip. | | 3. (continued)<br>ii) Magnitudes of, and reasons for, deviations from predicted behaviour (major and minor).<br>iii) Essentially continuous refinement of predicted future behaviour (see 1 above).<br>4. Include in analysis, simulation and testing the effects of:<br>i) Failures and errors (e.g. leaving a heater on when it should be off or vice-versa).<br>ii) Non-standard situations, particularly related to the power S/S and to attitude.<br>This should start in design phase, and continue throughout life (see 3 above).<br>5. Pre-launch testing should cover a much wider range of temperatures. The "expected ± 15°C" used on CTS/Hermes was insufficient due to assumptions and inaccuracies in predictions, and changes in operations from those assumed pre-launch. |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 10.8 | Eclipse Transients (every eclipse) | 1. The speed and magnitude of thermal transients (particularly on the light-weight solar arrays) at eclipse entrance and exit, and their effects (particularly on the power S/S) were not fully appreciated. | a. Contributed significantly to the loss of EPC A, increased eclipse operations complexity, loss of use of EPC OVC/ UVC, and suspension of SHF operations for two eclipse seasons (see 4.4).<br>b. Minor attitude/alignment perturbations at eclipse entry and exit.<br>c. Large amounts of time and manpower required to analyse this problem. | 8/11 | 1. Drastically upgrade analysis and test of thermal transients at eclipse entry and exit, and their effects on the rest of the S/C (particularly the power S/S). Note that the transient behaviour of light-weight, low thermal mass solar arrays is particularly critical and difficult. |
| 10.9 | Eclipse Operations (every eclipse) | 1. Power requirements of RCS heaters were excessive.<br>2. Thermal control heaters were not powered off the batteries.<br>3. No allowance was made in design, test or planning for long eclipses of the sun by the moon (theoretically up to 3 hours from entry into, to exit from, partial eclipse). | a. Contributed to battery problems (load shedding, etc.) in eclipse.<br>b. Lack of thermal control flexibility in non-standard situations.<br>c. Maximum eclipse experienced by CTS/Hermes was 93 minutes and design margins were sufficient. Potential major problems thermally in longer eclipses. | 8/11 | 1. Heaters must be broken up into small, separately commandable elements.<br>2. All heaters should be powered off the batteries (for use in emergencies).<br>3. Upgrade pre-launch predictions of possible eclipse occurrences. Design thermal S/S and operations to handle worst case prediction.<br>4. Use louvres and heat pipes to control the thermal environment. during eclipse (see 10.10). |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 10.10 | Non-standard Operations<br><br>These problems contributed significantly to the loss of the S/C on Day 330, 1979. | 1. Thermal design was critically dependent on thermal dissipation within the S/C.<br>2. Thermal behaviour in non-standard and attitude and power configuration was not known.<br>3. Power requirements of RCS heaters, and thruster preheat times, were excessive (see S/S 8). | a. When dissipating units were turned off (by UVS trip) the S/C cooled very rapidly. If components were not turned on again quickly, they became inoperable due to low temperatures, leaving no mechanism for thermal recovery.<br>b. The severity of this problem and the speed of response required were not recognized until it was too late.<br>c. High RCS heater power drain contributed to rapid loss of batteries (hence UVS) - see S/S 8. | 13 | 1. Use louvres to control heat dissipation from the S/C. Some form of automatic on-board control (with ground override) is required for non-standard emergency situations. Note that louvres have a significant impact on solar torques (when open), and that changing their orientation may also generate significant torques, requiring modification of the ACS.<br>2. Use heat pipes to distribute available heat to critical regions within the S/C. Again, this impacts ACS, as the fluid transfer in heat pipes can generate significant torques.<br>3. Drastically upgrade prediction of thermal behaviour in non-standard situations (see 10.7). |
| 10.11 | Variable Conductance Heat Pipes<br>(Day 075, 1977<br>Day 101, 1977<br>Day 253, 1977) | 1. Rapid overheating of the TEP OST. Believed to be due to:<br>2. Depriming of the heat pipes caused by the fluid freezing when the reservoir/pipes were shadowed by the S/C body for long periods. Note that freezing of heat pipe fluid was observed in pre-launch testing. | a. Several (relatively short term) interruptions in SHF communications.<br>b. Significant constraints on SHF communications:<br>i) Until the problem was analysed, uplink power to the TEP was limited at all times, and was removed when TM was lost.<br>ii) After analysis, uplink power was limited for ~12 hours per day during all eclipse seasons.<br>c. Excessive time and manpower required for analysis and testing. | 14 | 1. Include in design, analysis and testing of the whole thermal S/S, the effects of one part of the S/C shadowing another part. This is critically important for any heat pipes exposed to space.<br>2. If possible, avoid exposing any elements containing fluid directly to space. If this is unavoidable, very careful and detailed checking of the potential for, and the consequences of, freezing is required. |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 10.11 (cont) | Variable Conductance Heat Pipes (continued) | | d. Complex operations and procedures required (to protect against further occurrences), with occasional errors. | | 3. Upgrade analysis of non-standard situations (see 10.7). |
| 10.12 | Mass Properties (throughout life) | 1. Lack of data on thermal effects on mass properties (e.g. fuel transfer between tanks, variations in array shapes due to thermal effects, etc). | a. Uncertainties in mass properties (see 7.1). | 1 | 1. Upgrade analysis of thermal effects on mass properties. Improve communication of this data to operations group. |
| 10.13 | Alignment (throughout life) | 1. Inadequate data on thermal effects on alignment. Large thermal gradients made these significant (particularly for NESA's). | a. Uncertainties in magnitude and variability of component misalignments (see 7.2). | 1 | 1. Upgrade analysis of thermal effects on alignment. Improve communication of this data to operations group. |
| 10.14 | Apogee Motor (spin phase) | 1. Apogee motor heat soak-back duration was much longer than expected. | a. Temporary loss of one temperature sensor.<br>b. Batteries overheated-probably contributed to battery degradation (see 4.1).<br>c. NESA's overheated-possibly contributed to NESA-A problems (see 6.1). | - | 1. Improve conductance modelling of expended apogee motor.<br>2. Upgrade thermal isolation of critical components from A/M soak-back. |
| 10.15 | NESA's (summer solstice) | 1. The NESA's approached (and occasionally exceeded) qualification temperature during summer solstice.<br>2. The NESA-A anomaly appeared to be more likely at high temperatures. | a. Possibly contributed to NESA-A problems (see 6.1).<br>b. Potential for damage to both NESA's (would probably have been catastrophic). | 1 | 1. Include in thermal analysis the effects of multiple solar reflectance between angled surfaces.<br>2. Upgrade thermal analysis, design and testing of NESA's.<br>3. Modify thermal design to reduce the range of temperatures experienced by the NESA's, particularly at the high end. |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 10.16 | Batteries and Charge Controllers (throughout life)<br><br>See S/S 4. | 1. Battery temperature design limit was too high.<br>2. Battery B ran hot due to a heat path to the aft platform (mis-positioned battery mounting post).<br>3. Both batteries ran hot, particularly in overcharge.<br>4. Temperature difference between batteries was excessive.<br>5. Temperature spread between cells was excessive, on both batteries.<br>6. Charge controllers could not handle thermal dissipation at high voltage, high current charging (e.g. both batteries at C/10).<br>7. Reconditioning resistor was not thermally qualified for use in sunlight.<br>8. Battery thermal data was inadequate. | a. Contributed significantly to large-scale degradation in battery capacities, largely irreversible, throughout life.<br>b. Contributed significantly to serious mismatch between batteries.<br>c. Complex operations and procedures required, causing occasional errors, which added to the degradation.<br>d. Excessive time and manpower required to manage batteries, etc. | 1/8/9/10 | 1. Drastically upgrade thermal design, analysis and testing of battery system. Specifically, do not use a single node approach.<br>2. Possibly use a shunt regulated system.<br>3. Use heat pipes to minimize temperature differences between battery cells and between batteries.<br>4. Maintain battery temperatures between 0°C and 15°C using thermostatically controlled heaters and louvres. Temperature limits must be adjustable, perhaps using on-board programmable microprocessors.<br>5. Do not fly changes in structure without complete evaluation of thermal impact.<br>6. Upgrade design and testing of charge controller so it can handle high charge rates at high voltages.<br>7. Position and qualify reconditioning resistors to be usable at any orbit slot.<br>8. Cell-by-cell battery temperatures should be available. |
| 10.17 | Experiments Power Converter A (Day 064, 1976) | 1. The internal coils of a high power relay were not properly heat sunk. | a. Probably contributed to damage to relay, leading to loss of EPC-A (see 4.4). | 11 | 1. Upgrade thermal design and testing of high power relays. |

Subsystem #10: Thermal (continued)

| UOE/SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 10.18 | Telemetry Transmitters (throughout life) | 1. Thermal expansion in the subtrate caused impedance mismatch.<br>2. Transistor in high power stage ran hot.<br>3. Other S/C operations (e.g. heaters, RCS, batteries) had unexpectedly large impact on transmitter output power. | a. Highly likely that loss of Tx A, and degradation of Tx B, were caused by these problems (see 3.1 and 3.2).<br>b. Step-decreases in Tx output due to other S/C operations (some permanent, most short-term). | 1/8 | 1. Drastically upgrade thermal design, analysis and testing of transmitters.<br>2. All testing of all components must include continuity testing during temperature transitions. This is particularly important during tests involving the complete S/C.<br>3. Testing of critical components should include a much larger number of thermal cycles. If possible the number and magnitude of the cycles should approximate those that the component will experience on-orbit (i.e. thermal cycle life testing is required).<br>4. Upgrade analysis, testing and prediction of thermal effects of S/C operations on critical components (see 10.7). |
| 10.19 | SHF Transponder (throughout life) | 1. Changes in thermal dissipation in 20W TWT when drive removed caused out-gassing.<br>2. Many indications of temperatures exceeding limits, without indicating a real problem.<br>3. Thermal gradients in 20W TWT caused instability in resistive divider, making PWM 50V voltage vary anomalously. | 1. Arcing in the connector, causing 20W TWT to trip off (see 1.1).<br>2. Confusion, reduction in credibility of limits, etc. Potential for error.<br>3. Uncertainty; time and manpower required to deduce data from other sources. | 14 | 1. Upgrade analysis of thermal effects of drive removal on all TWT's.<br>2. Upgrade analysis and prediction of expected thermal behaviour, and communication of this data to operations group (see 10.7).<br>3. Upgrade analysis and testing of thermal effects on sensors. Do not fly unreliable sensors. |

Subsystem #10: Thermal (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 10.20 | Beacon (throughout life) | 1. Unexpected (but within spec.) variations in frequency and power with temperature.<br>2. Apparent inability to achieve high power at eclipse exit (once). Possibly due to loss of gain at low temperatures. | a. Uncertainty; time and manpower required for analysis.<br>b. Minor difficulties for SHF beacon experimenters. | 14 | 1. Upgrade analysis/testing of expected effects of thermal variations (as opposed to meeting spec.).<br>2. Better communications of such data to operations group. |
| 10.21 | RCS (throughout life) See S/S 8 | 1. Possible valve seat swelling and other degradations due to high temperatures.<br>2. Two-phase flow in lines and/or chambers due to excessive heat soak-back from thruster firings.<br>3. Possible freezing of hydrazine due to low temperatures.<br>4. Excessive power required for RCS heaters.<br>5. Auto-decomposition of hydrazine was significantly increased by high temperatures, and frequent, wide-range temperature cycles.<br>6. Inadequate temperature data due to missing or improperly placed sensors, failures, and non-redundant Encoders.<br>and various others (see S/S 8). | a. Contributed significantly to LTE degradation and gas formation.<br>b. May have contributed significantly to loss of one LTE.<br>c. Large uncertainties in fuel used/remaining, performance analysis, mass properties, etc.<br>d. Excessive time and manpower for data gathering, analysis, etc.<br>e. Constrained and complicated major operations.<br>f. Increased risks and complexity in attitude reacquisitions and eclipses.<br>and many others - see S/S 8. | 1/4/5/6/ 8/12/13/ 15 | 1. RCS thermal control <u>must</u> be integrated (in design, analysis simulation and testing) with S/C thermal control system.<br>2. Upgrade thermal design of RCS to:<br>i) Reduce extremes (particularly the high end) of temperatures.<br>ii) Reduce temperature cycling.<br>iii) Simplify control procedures.<br>3. See S/S 8, particularly 8.3, Recommendations 2, 8.5, 8.6, 8.7.<br>4. See 10.1, 10.2, 10.3, 10.4, 10.5, 10.6, 10.7. |
| 10.22 | Array Angle Encoders (throughout life) | 1. Loss of two data bits on one encoder, believed due to low temperature marginal performance, as seen in pre-launch test. | a. Ambiguity and confusion re array orientation, particularly after attitude anomalies. | 1/11/13 | 1. Avoid using components that perform marginally in pre-flight test.<br>2. Upgrade thermal design, analysis and test of array angle encoders. |

Subsystem #11: SATE, TEC, S/C Charging, etc.

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 11.1 | Secondary Power Converter (Day 273, 1976 Day 079, 1977) See S/S 4 | 1. SPC-A tripped off. Believed to be due to problems in SATE and/or a transient caused by S/C charging. | a. Loss of all secondary modules (hence TM).<br>b. Complex and uncertain recovery procedures.<br>c. Risk of damage to several components (see 4.7).<br>d. Potentially catastrophic if not recognized (e.g. in zero-TM) because of loss of array tracking. | 1 | 1. Upgrade protection against S/C charging, and the effects of transients (see 11.4).<br>2. Upgrade analysis and testing of effects of transients (see 11.4).<br>3. See 4.7. |
| 11.2 | Solar Array Technology Experiment (SATE) (Day 073, 1977 Day 075, 1977 Day 079, 1977) | 1. SATE secondary module tripped off twice.<br>2. Complete loss when SATE secondary module could not be turned on after an eclipse.<br>Causes are uncertain but it is believed that:<br>3. The SATE trip-offs were due to transients caused by S/C charging.<br>4. The loss of SATE was due to damage in SATE, the Transient Event Counter (TEC) and/or the SATE secondary module (which also powered the TEC) caused by these transients.<br>5. The damage may have been due to inadequate isolation of SATE and/or TEC and/or SATE secondary module from the effects of the transients the TEC was designed to monitor. | a. Loss of most SATE data.<br>b. Significant reduction in measurement of life-time affects on arrays (material degradation, shape changes, etc.).<br>c. Complex and risky procedures required to measure array power capability (see 4.6).<br>d. Possibly caused SPC-A trips (see 11.1).<br>e. Loss of all data on transients. Note that attempts were being made to correlate this data with:<br>i) Environment (e.g. solar storms, etc.).<br>ii) S/C events (e.g. special operations, anomalous occurrences, etc.). | 1/11 | 1. Upgrade protection against S/C charging, and the effects of transients, particularly in any devices deliberately designed to detect transients (see 11.4).<br>2. Upgrade analysis and testing of effects of transients (see 11.4). |

Subsystem #11: SATE, TEC, S/C Charging, etc. (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 11.3 | Solar Array (Day 160, 1976) | 1. Arcing on the pallet diode board, believed due to S/C charging. | a. Permanent loss of ~15% of experiments array power.<br>b. Significant, short-term attitude perturbations.<br>c. Significant time and man-power required for analysis. | 1 | 1. Arrays must be designed with backside shielding approximately equivalent to the front side. Possible methods include:<br>i) Add a conductive grounded layer to the back side.<br>ii) Use a thin aluminum honey-comb substrate. |
| 11.4 | S/C Charging in General (throughout life) | Several anomalies on the S/C are believed to have been caused by, or related to, S/C Charging and/or transients caused by charging. These include:<br>1. SPC-A trip-off (see 11.1).<br>2. SATE/TEC secondary module trip-off (see 11.2).<br>3. Arcing on solar array (see 11.3).<br>4. Spontaneous Heater E turn-on (Day 278, 1977) (see 8.12).<br>5. Possibly MWC switch at NESA-A turn-on (Day 277, 1978) (see 6.8).<br>6. Possibly NESA-A anomalies (Days 100, 101 and 143, 1976; Days 227 and 322, 1977; Days 120, 237 and 330, 1979) (see 6.1).<br>7. Possibly "pitch glitches" (see 6.3). | Consequences of these occurrences varied from neglibible (MWC switch) to potentially catastrophic (NESA-A anomalies) - see referenced sections for details. | 1/7/11/13 | 1. Use command and data line interface circuits which provide protection against short, high level transients.<br>2. Bond all second surface mirrors with conductive adhesives.<br>3. Properly ground all layers of thermal blankets.<br>4. Ground all metal parts.<br>5. Drastically upgrade EMI testing at the S/C level, using a very fast spark source. Results of E/M tests should be used to specify EMI protection of flight components.<br>6. Emission and susceptibility levels of telemetry and command lines should be tightly limited by EMI spec. |
| 11.5 | Electro-magnetic Interference (throughout life) | 1. Several of the problems (e.g. trip-offs, etc.) listed in 11.4 may have been due to EMI not necessarily originating in S/C charging.<br>2. It is believed that several 20W TWT trip-offs were due to EMI (from arcing in the connector) on the trip circuits. | a. See 11.4<br>b. See 1.1<br>c. See 12.5 | 1/7/11/13/14 | 1. See 11.4<br>2. Redesign 20W TWT connector.<br>3. Upgrade analysis of 20W TWT potential for out-gassing when drive removed. |

Subsystem #11: SATE, TEC, S/C Charging, etc. (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 11.5 (cont.) | Electro-magnetic Interference (continued) | 3. Fluctuations on the SHF transponder 76V bus current TM are believed to have been caused by EMI from the TEP uplink. | | | |
| 11.6 | SATE Telemetry (until Day 079, 1977). | 1. SATE temperatures did not correspond to array temperatures because dummy cell over sensor was thermally different from main power cells.<br>2. Array deflection sensor data did not correlate with other data, due to mixed up sensors/calibrations. | 1. Inaccurate data on array thermal behaviour made power measurements, etc. less cetain and more complicated.<br>2. Loss of data until confusion resolved. | 1 | 1. Ensure all sensors are measuring representative data.<br>2. Upgrade identification and control of similar but non-identical units.<br>3. Include checks of identities of such units in S/C testing. |
| 11.7 | TEC Telemetry (until Day 079, 1977) | 1. Three separate lines were monitored, each for 1 second in 4 (the fourth sample was a synch word).<br>2. A single counter was used with:<br>i) re-zero at the start of each second's counting,<br>ii) overflow above 63 counts.<br>3. There was no indication of the environment external to the S/C. | a. Much of the available data was lost.<br>b. Excessive ground processing was required to interpret the results.<br>c. Correlation with disturbances in the magnetosphere were very questionable due to the possibility of highly localized major perturbations.<br>d. Any noise on the downlink (due to e.g. Tx problems) made the data virtually useless. | 1 | This could have been extremely useful in analysing S/C anomalies (e.g. see 11.4 and 11.5). Major improvements required include:<br>1. Carry an external electromagnetic environment monitor.<br>2. Use separate counters/registers for each line being sampled.<br>3. Do not rezero registers after sampling.<br>4. Use TM clock for timing.<br>5. Expand size of registers.<br>In addition, it appears likely that it would be extremely useful to carry additional sensors. |

Subsystem #12: Transmitter Experiment Package

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 12.1 | TEP Trip-offs (13 in 1976 1 in 1977 2 in 1978) | 1. Trip-offs of TEP.<br>Believed to be due to:<br>2. Uplink overdrive<br>3. Uplink frequency below band. | a. Short-term interruptions to SHF communications.<br>b. Potential damage to tube and high power circuits with cycling under load.<br>c. Time and manpower required for analysis.<br>d. Loss of essential data (when no TM). | 1/14 | 1. Better control of uplink required. Note that this is a very complex problem on multi-user S/C.<br>2. Possibly build-in limiters (power and frequency) on-board. |
| 12.2 | Variable Conductance Heat Pipes (Day 075, 1977 Day 101, 1977 Day 253, 1977) | 1. Rapid overheating of the TEP Output Stage Tube (OST).<br>Believed to be due to:<br>2. Depriming of the heat pipes caused by the fluid freezing when the reservoirs/pipes were shadowed by the S/C body for long periods. | a. Short-term interruptions to SHF communications.<br>b. Significant constraints on SHF communications availability and uplink power, particularly:<br>i) Around eclipse season (for ~12 hours/day)<br>ii) When TM was not available.<br>c. Risk of damage to OST.<br>d. Complex operations and procedures required to protect against further occurrences, with occasional errors.<br>e. Excessive time and manpower required for analysis. | 1/14 | 1. Include in thermal design, analysis and testing the effects of one part of the S/C shadowing another.<br>2. If possible, do not expose heat pipes directly to space. If this is unavoidable, very careful checking of the potential for, and consequences of, freezing is required. Note that this is very difficult due to the differences in behaviour of heat pipes in zero-g vs on the ground.<br>3. Possibly modify heat pipe design (e.g. different fluids, etc.).<br>4. Better control of uplink required. |

Subsystem #12: Transmitter Experiment Package (continued)

| UOE/SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 12.3 | TEP Trip Indicator (throughout life) | 1. TEP trip indicator was not always easily understood (e.g. internal envelope pressure indicated as cause of trips believed due to below band uplink). | a. Confusion; time and manpower required for analysis. | 1/14 | 1. Upgrade analysis and documentation of trip causes and effects.<br>2. A multi-purpose trip indicator appears to be very useful, but ground S/W should provide flags and/or messages (e.g. limit checks on the various levels, rather than a single check) to provide simple and fast recognition/identification of a trip. |
| 12.4 | Spurious Signals (throughout life) | 1. Without TM, trips were difficult to identify precisely.<br>2. TEP had to be on to provide the second spurious signal.<br>3. The spurious signals varied in strength with the uplink. | a. Complex command sequences required to cover the various possibilities.<br>b. Extra cycling of tubes.<br>c. Potential for errors.<br>d. Some confusion in interpreting data. | 1/14 | The spurious signals (originating in the SHF Rx, one transmitted by the 20W TWT, the other by the 200W tube) were extremely useful when TM was bad/unavailable. If TM cannot be guaranteed, some consideration should be given to providing spurious signals (or their equivalent, i.e. transmissions that exist without an uplink) with the following characteristics:<br>1. No dependance on uplink, except possibly, a change in level (not to zero) at a trip or turn-off.<br>2. One such signal per steerable antenna, and one via a fixed antenna, all with relatively narrow beamwidths (compared to the Beacon).<br>3. Clearly defined relationships between signal strength and antenna pointing/attitude.<br>4. If possible, these signals should be powered from the batteries when array power is unavailable. |

Subsystem #12: Transmitter Experiment Package (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 12.5 | TEP Uplink (throughout life) | 1. The SHF transponder 76V bus current telemetry fluctuated due to noise from modulation on the TEP uplink. Observed in pre-launch testing. | a. Uncertainty, potential for errors.<br>b. Time and manpower for analysis. | 1/14 | 1. Do not fly unreliable TM. If it is unavoidable, improve communication of expected behaviour to operations group.<br>2. Improve EMI protection of TM channels (see 11.5). |
| 12.6 | TEP Power Monitors (throughout life) | 1. TEP reflected power monitor inoperative. Observed in pre-launch testing.<br>2. TEP forward power monitor had to be modified for temperature, voltage and current variations. Several updates on the algorithms were required. | 1. Loss of data; some confusion.<br>2. Inaccurate and misleading data. Significantly impacted calculation of array power capability. Considerable time and manpower required to modify S/W. | 1/14 | 1. Do not fly unreliable TM. If it is unavoidable, improve communication of expected behaviour to operations group. Perhaps S/W should be modified to remove misleading data from displays.<br>2. Calibration system must allow for functional dependance of one telemetered parameter on others. Detailed, accurate data on such interdependence must be provided to the operations group (particularly the S/W designers) early in mission planning. |
| 12.7 | Surge Currents (throughout life) | 1. Large capacitance in TEP led to large surge currents (e.g. when array switch closed). | a. Contributed to loss of EPC-A (see 4.4).<br>b. Risk of damage to other components. | 11/14 | 1. Upgrade analysis and testing of transients and their effects.<br>2. Possibly require a shunt regulator on the bus supplying the TEP. |

Subsystem #12: Transmitter Experiment Package (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 12.8 | Ground Received Signal Strengths (throughout life) | 1. SHF GRSS's showed significant variations due to weather, ground equipment problems, precision and frequency of ground antenna updates, etc. | a. Uncertainties in using SHF signals to monitor S/C (particularly when no TM).<br>b. Time and manpower required for analysis. | 1/14 | 1. See 12.4.<br>2. Improve prediction of expected behaviour, and communication of this data to operations group.<br>3. Upgrade ground equipment and operation. Perhaps use auto-track on antennas. Note that care must be taken to minimize water in ground waveguides. |
| 12.9 | Terminating Communications (throughout life) | 1. Inadequate means of terminating communications. | a. Occasional undesirable extensions of experiments.<br>b. Improper commands used to terminate an experiment, with slight risk of damage. | 14 | 1. Better control of uplink required.<br>2. Study needed of requirements for, and feasibility of, safe methods of shutting down communications on the S/C. |

Subsystem #13: Ottawa Ground Station Non-Computing Hardware

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 13.1 | S-Band Uplink System (throughout life)<br><br>Note that these problems may have contributed to the S/C loss. | 1. Occasional loss of uplink lock due to:<br>2. Improper updating of ground antennas,<br>3. Ground station hand-over (to NASA support station).<br>4. Ground power failures.<br>5. S/C attitude anomalies, loss of power, etc.<br>6. Unknown other causes (possibly S/C and ground EMI; interference from sun, other S/C, or other ground stations; etc.). | a. Loss of commandability.<br>b. Step change in S/C Rx frequency, making re-acquisition of lock difficult.<br>c. Step change in S/C Tx frequency, causing loss of downlink lock, and hence of all S/C data.<br>d. Very difficult to detect, and to verify, re-acquisition of lock, because downlink lock was lost at the same time.<br>e. Major S/C problems, particularly following attitude anomalies. | 1/13/18 | 1. Upgrade prediction of ground antenna pointing requirements, and method of updating, Perhaps auto-track should be used, while a downlink is available, with a programmable micro-processor to control pointing when no downlink signal.<br>2. Ground Tx frequency should be maintained as close as possible to S/C Rx rest frequency.<br>3. An automatic uplink frequency sweep system should be readily available. The system must be carefully matched to the S/C Rx characteristics.<br>4. Upgrade station hand-over procedures.<br>5. Improve protection against the effects of ground power failures. |
| 13.2 | S-Band Downlink System (throughout life)<br><br>Note that these problems contributed significantly to S/C loss. | 1. Loss of downlink lock, and occasional spurious lock on a side-band due to:<br>2. Improper updating of ground antennas.<br>3. Station hand-over (to NASA support station).<br>4. Interference from sun.<br>5. Interference from other satellites.<br>6. Ground power failure.<br>7. S/C attitude anomalies, loss of power, etc.<br>8. Low power from S/C Tx.<br>9. Loss of uplink lock (see 13.1).<br>10. Unknown other causes (possibly S/C and ground EMI, etc.). | a. Loss of all S/C data.<br>b. Step change in ground Rx frequency, making re-acquisition of lock difficult.<br>c. Extreme difficulty in verifying uplink lock. | 1/13/18 | 1. See 13.1, Recommendation 1,4,5.<br>2. If feasible, ground Rx frequency should remain fixed when lock is lost.<br>3. The whole up-down closed loop should be designed so that the S/C Tx frequency is always as close as possible to its rest frequency.<br>4. An automatic ground Rx frequency sweep system should be readily available. Note that the equivalent effect may be obtained by sweeping the uplink, provided uplink lock is acquired and maintained. |

Subsystem #13: Ottawa Ground Station Non-Computing Hardware (continued)

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 13.6 | SHF Beacon (Day 073, 1977) | 1. Difficulty in attaining high power indication, possibly due to locking on a side-band. | a. Additional cycling of beacon.<br>b. Time and manpower required for analysis. | 11/14 | 1. Upgrade prediction and testing of beacon frequency variations with temperature.<br>2. Upgrade ground procedures, possibly including an automatic frequency sweep. |
| 13.7 | Ground SHF Transmitters (throughout life) | 1. Trip-offs of the 200W and the 20W TWT's due to uplink overdrive. | a. Short-term interruptions to SHF communications.<br>b. Potential damage to tubes and high power circuits with cycling under load.<br>c. Loss of critical data (when no TM).<br>d. Time and manpower required for analysis. | 1/14 | 1. Improve control of uplink, perhaps by building output power limiters in ground transmitters.<br>2. Upgrade ground station procedures and documentation. |
| 13.8 | Signal Instruction Generator (throughout life) | 1. Occasional commands rejected due to SIG H/W problems.<br>2. Diagnostic messages were not accurate in these cases. | a. Commands delayed or not executed. Minor effects on S/C, but potentially catastrophic.<br>b. Switch to redundant SIG sometimes required. | Various | 1. Upgrade regular testing and maintenance of ground equipment.<br>2. Build in checks on all critical ground equipment, with feedback to the computer, so faults can be identified before the equipment has to be used.<br>3. Upgrade diagnostic messages from computer. |
| 13.9 | Strip Chart Recorders (throughout life) | 1. Occasional mechanical problems (loss of pens, paper jams, etc.), sometimes with long time delays before replacement parts available.<br>2. Inadequate calibration.<br>3. Confusing, hard to read time code.<br>4. Occasionally left off (after being in standby due to no TM). | a. SCR's were critically important to on-line operations and to off-line analysis because:<br>i) Other data recording/playback capabilities were totally inadequate. | All | 1. Earlier recognition of significance of SCR's, with upgrading of testing, maintenance, and spare parts inventory.<br>2. Regular, systematic scaling and calibration required.<br>3. Control and monitoring of chart speeds and on/off status from the computer appears preferable. |

Subsystem #13: Ottawa Ground Station Non-Computing Hardware (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 13.9 (cont) | Strip Chart Recorders (continued) | 5. Frequent changes in chart speeds and pen assignments were required, but charts were often not annotated completely and correctly.<br>6. Totally inadequate reserve SCR capability (for non-archival recording during special events, tests, etc.). | ii) Noisy data made non-graphical displays virtually useless.<br>Any reduction in completeness, accuracy, and readability of data complicated operations and analysis, and, in a few instances, increased risks to the S/C (e.g. risk of not recognizing a NESA-A anomaly in time to respond). | | 4. If feasible, a system for automatic printing on the SCR's would be a significant improvement. Controlled by the computer, such a system would automatically mark the chart paper with pen assignments, chart speeds, and times (in normal alphanumerics), on instruction from the operator, and at any changes.<br>5. Provisions must be made for reserve SCR capability of high quality and reliability for special purpose data recording. |
| 13.10 | Equipment Configuration (throughout life) | 1. Configuration of patch panels, etc. was badly defined and confusing, particularly when changes were required for:<br>i) Analogue tape replays.<br>ii) Real-time simulations.<br>iii) Switching a piece of redundant equipment (e.g. LP) to on-line use. | a. Significant time delays in changing equipment configuration.<br>b. Uncertainty, with occasional errors, in returning to standard configuration.<br>c. Degradation of patching H/W due to frequent switching. | 1/16/17 | 1. Drastically upgrade documentation of patching/switching system, including detailed diagrams of all frequently used modes.<br>2. Once the required modes are established, perhaps a simplified mode switching system could be implemented.<br>3. Possibly some form of logic switching (vs H/W patches) would be preferable. |
| 13.11 | Timing Mechanisms (throughout life) | 1. Time-code errors:<br>i) Early in life.<br>ii) When replaying analogue tapes.<br>iii) When using NASCOM data, (particularly when switching to or from). | a. Some computer crashes.<br>b. Some S/W useless when time codes wrong. | Various | 1. Upgrade clock/computer interface, design, testing and maintenance.<br>2. Use local clock, rather than time code included in NASCOM data block.<br>3. Possibly provide some form of filtering on time-codes used by computer. |

Subsystem #13: Ottawa Ground Station Non-Computing Hardware (continued)

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 13.12 | Power Supply (throughout life) | 1. Occasional power losses (particularly due to thunderstorms).<br>2. Significant time-delays in switching to back-up power.<br>3. Occasional lack of back-up power due to lack of fuel. | a. Computer crashes (loss of all data, and of standard mode commanding).<br>b. Recovery occasionally took excessive time.<br>c. Potential damage to various pieces of equipment.<br>d. Occasional loss of climate control for extended periods. | All | 1. Upgrade backup power system, perhaps by including battery and/or capacitive storage to reduce the effects of transients, and to carry the system until the generator could come on-line.<br>2. Upgrade ground equipment maintenance. |
| 13.13 | S-Band Reception (most of life) | 1. Antenna/Tx gain was too low to allow data decommutation when S/C Tx in low power mode. | a. See 3.1, 3.2 | All | 1. This was not predictable - system had ample margin if the S/C Tx had performed within spec. or near it. |
| 13.14 | Command System (throughout life) | 1. Occasional commands not executed due to wrong equipment configuration (e.g. 70 kHz off). | a. Relatively minor effects (e.g. O/T Armed and AFP Enabled through a sun interference caused attitude perturbations but no damage). Potentially catastrophic. | Various (e.g. 7) | 1. Build in checks on all critical ground equipment, with feedback to the computer.<br>2. Upgrade ground operations. |
| 13.15 | Analogue Tape Recorder (early in life) | 1. Major problems with noise in replaying analogue.<br>2. Problems obtaining data at switchovers between tapes.<br>3. Many time-code errors in replaying tapes. | a. Difficulty in obtaining data for analysis of anomalies, etc.<br>b. Excessive time and manpower required. | 13 | 1. Given the general inadequacy of data replay capability, this was a very important function. A good tape record/playback facility is essential throughout life.<br>2. Tape recordings should overlap by a significant time (~5 minutes).<br>3. Improved recording/playback of time codes is required, possibly with a filter on the codes used by the computer. |

Subsystem #13: Ottawa Ground Station Non-Computing Hardware (continued)

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 13.16 | SHF Signal Acquisition (last year of life) | 1. SHF receivers had a 100 sec sweep time.<br>2. Occasional minor problems with receive system H/W. | a. Excessive time delays in acquisition (e.g. at turn-on post-eclipse).<br>b. High risk of not acquiring signals after attitude anomalies.<br>c. Occasional loss of access to one of the SHF signals. | 11/13/14 | 1. Use receivers with much shorter sweep times. Note that this has significant implications on the whole antenna/receiver system.<br>2. Note that the SHF signals were extremely useful throughout life, and became critically important when TM was lost. Equipment reliability, spare parts, testing and maintenance should be upgraded to reflect this. |
| 13.17 | Documentation (throughout life) | 1. Documentation was inadequate. Specifically:<br>i) Detailed operations schedule was frequently not available for review, particularly when late changes were made.<br>ii) Mission operations log frequently omitted commands, did not list anomalies and unusual events, did not provide descriptions of operations, etc.<br>iii) Discrepancy reports were incomplete, and review and disposition was inadequate.<br>iv) H/W description, configuration control, test procedures, etc. were minimal. | a. Occasional errors in operations schedule (fortunately none with severe impact).<br>b. Significant problems in tracking operations, and analyzing S/C behaviour.<br>c. Significant difficulty in analyzing and correcting problems.<br>d. Dependance on specific individuals with specialized knowledge.<br>e. Significant difficulties in changing H/W configuration. | All | 1. On-line/off-line data processing systems should include an automated command log, with all commands, descriptors, etc. available.<br>2. Detailed operations schedules should be prepared several days in advance, with a mechanism for review of any changes.<br>3. A complete set of documentation on ground H/W, test procedures, status, etc. is essential.<br>4. An adequate mechanism for generation, analysis, review and disposition/correction of discrepancies is essential. |

SUBSYSTEM: #14 OTTAWA GROUND STATION COMPUTING HARDWARE

| UOE/SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 14.1 | HP2100/MX on-line computers | - generally inadequate for their task<br>- core limited/too slow | - extensive and expensive non-standard OS-executive development required<br>- system not ready by launch | 1,18 | - size computer requirements before specification or purchase of hardware/software |
| 14.2 | HP 2115/2116 interface computer | - interface with NASA and real time simulation overlooked<br>- data source to debug HP2100's overlooked | - inadequate computers/ programs<br>- system not ready by launch<br>- non applications programming required | 1, 17 18 | - size computer requirements before specification or purchase of hardware/software |
| 14.3 | HP2100/MX attitude acquisition on-line computers | - GCAP required radically different configuration compared to on-line system | - confusion and redundant effort in implementing ground station | 13, 18 19 | - integrate requirements of individual phases of the Mission into a total hardware requirement and plan. |
| 14.5 | HP2100/MX I/O Capability | - no magnetic tape input interface in system | - difficulty in transferring data from other computers to HP2100 | 1, 16 | - either eliminate need of intercomputer communication or provide standard I/O capability. |

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SUBSYSTEM: #15 OTTAWA GROUND STATION SOFTWARE

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 15.1 | Thruster Firing Control (TFC) Program | - Hardware/software could not handle duty cycles of one second or less | - SIG tied up from minutes to an hour<br>- ordinary housekeeping commands could not be sent | 5, 6 12 | - future system hardware/ software should be capable of high duty cycles |
| 15.2 | Keyboard Command Interpreter | - operator requirement to remember float-point, fixed-point, octal, hexadecimal input formats | - confusion<br>- delayed commands | mission | - command software should automatically handle various types of parameter input. |
| 15.3 | Calibration Coefficients | - only form allowed was polynomial expansion | - large observed errors in engineering units of several variables | mission | - computing system should be capable of allowing several forms of calibration. |
| 15.4 | Calibration Coefficients | - lack of calibration data on several variables | - confusion in comparing raw and calibrated data | mission | - all calibration data should be rigorously documented during hardware test<br>- final list of computed curves versus hardware/test curves required. |
| 15.5 | MDWMP, EWSK Other software programs | - susceptable to bad data | - erroneous prompts and messages | 4,5 | - ensure adequate telemetry<br>- analyse desirability of extensive data filtering |
| 15.6 | APPL-DAT data handling program | - no magnetic tape input interface in system | - required paper tape read function<br>- too susceptible to tearing/ damage<br>- required paper tape punching on $\Sigma$9 off-line | 1, 16 | - future on-line ground station computers should have standard data I/O capability to interface with off-line computers. |

SUBSYSTEM: #15 OTTAWA GROUND STATION SOFTWARE

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 15.7 | S/C Switching Model | - no adequate model available<br>- attempt to implement a version on HP 2100 frustrated by system inadequacy and lack of resources | - staff/controllers never adequately aware of ON/OFF status of the S/C | mission | - on-line computing system should be able to adequately compute ON/OFF status of S/C |
| 15.8 | S/C Switching Model - LIM CHECK | - switching model never adequately implemented<br>- interaction with LIM CHECK not used | - all limit checks had to be set by operator command<br>- no automatic setting capability | mission | - an on-line switching model should properly interface with the limit checking routines. |

SUBSYSTEM: #16 NASA/STDN HARDWARE/SOFTWARE

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 16.1 | NASA/Ottawa Interface | - Omitted in original planning<br>- Mission critical due to telemetry problems<br>- duty controllers/staff unfamiliar with protocol | - adequate hardware/software support late and complicated<br>- confusion in verbal/telephony communication | mission | - include in early Mission planning<br>- assess data blocking requirements on interface hardware/software<br>- train staff on verbal inter-action with NASA |

SUBSYSTEM: #17 - SYSTEMS PLANNING, TEST AND ANALYSIS

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 17.1 | Systems Mission Planning | Lack of early and sufficient systems planning and manpower | DOP's and HP 2100 software not ready for start of On-Orbit Phase of Mission | 18 | - Long range system planning required at outset of program<br>- Personnel functional overlap and continuity required |
| 17.2 | Systems Test Planning | Minimal systems input to spacecraft test | Incomplete test/hardware information in DOP's and software | 18 | - Systems/Operations interface with S/C, ground station design and test personnel required |
| 17.3 | Spacecraft Test Planning | Lack of early and sufficient test planning and manpower | Several hardware problems overlooked<br>17.3.1 NESA A Anomoly<br>17.3.2 Heat pipe freeze up<br>17.3.3 RCS problems<br>17.3.4 Transmitter B degradation<br>17.3.5 Battery UVS problems<br>17.3.6 Battery B-heat leak | 18 | - long range Test Planning required at outset of program<br>- personnel functional overlap and continuity required<br>- test, plan and procedures required for auditing well in advance of test occurrence |
| 17.4 | Ground Station Duty Controller Planning | Duty Controller trained on the job. | Initially DOP's and schedules not adequately followed | 18 | - on an experimental satellite the chief duty controllers should start training during S/C test phase |

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SUBSYSTEM: #17 SYSTEMS PLANNING, TEST, AND ANALYSIS

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 17.5 | Flight Directors | Inexperienced and under trained personnel at beginning of On-orbit phase. | Duty controllers intimidated by other personnel and flight directors allowed deviation from DOP's. | 18 | - increase training/experience of duty controllers<br>- delineate responsibility and authority for all Mission events/operations. |
| 17.6 | Mission Computing Requirements | Lack of early and technical assessment of complete computational load requirements | - too many different types of computers<br>- several computers inadequate to task<br>- operations/events/test compromised | 3, 13, 16, 17, 18 | - determine computational requirements well before launch and before computing system specified. |
| 17.7 | Switching Model of the Spacecraft | - no adequate model for ON/OFF states of S/C components<br>- only design blueprints available<br>- HP2100 model attempted but never used because of lack of resources/ test | - staff/controllers never adequately aware of ON/OFF status of the S/C | mission | - an adequate switching model of the spacecraft should be implemented and debugged on the on-line system.<br>- such a switching model would be invaluable for any future requirement for automatic ground controlled switching. |
| 17.8 | Ground station hardware/ software implementation | - limited capability for system to be modified or extended<br>- difficulty in planning for all on-orbit eventualities<br>- system completed well after launch | - barely adequate on-line system at launch<br>- no possibility of modifying system after launch to reflect flight operations experience<br>- no opportunity to interact with the S/C test program | mission | - the initial version of the on-line system should be implemented and debugged by S/C test<br>- the system must be sized/ scoped to allow for straight forward modification and extension<br>- the system should ultimately be commissioned by test procedures using a real-time simulation. |

SUBSYSTEM: #17 - SYSTEMS PLANNING, TEST AND ANALYSIS

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 17.9 | Detailed Operating Procedures DOP Standard Procedures | - lack of experienced systems personnel<br>- lack of system, test, design interface<br>- schedule, resource problems<br>- lack of rehearsal, training with DOP's at Ground Station | - incomplete DOP's at launch<br>- incorrect operation of the spacecraft<br>- DOP's difficult to follow by untrained duty controllers | On-Orbit | - preliminary DOP's for all known standard events should be available for review well before launch<br>- all personnel, DOP's should be tested at the ground station using a real-time simulation<br>- experienced personnel are mandatory for DOP/system planning<br>- technical documentation staff is recommended |
| 17.10 | Non-Standard Procedures and Software | - lack of experienced systems personnel<br>- given very little emphasis<br>- virtually ignored as to on-line computing requirements<br>- lack of failure modes and effects analysis in design and test | - lack of adequate procedures or software by time of first attitude reacquisition<br>- need for redundancy in essential, functions never properly verified by test<br>- AFP O/T inhibit not properly assessed resulting in eventual loss of S/C | On-Orbit | - analysis of modes and effects should begin early and parallel the design process<br>- preliminary NSP's for all critical failure modes should be available for comment well before launch<br>- all NSP's and software should be tested at the ground station using a real-time simulation |

SUBSYSTEM: #17 - SYSTEMS PLANNING, TEST AND ANALYSIS

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 17.11 | Mission Computer Hardware/Software Specification | lack of adequate hardware/software selection planning to implement computational load requirements | - several different and inadequate computers specified essentially on an ad hoc basis<br>- operations/events/test compromised<br>- see Table 1 for a list of computers used during the Mission | Mission | - modern computing technology and analysis would allow all required on-line, off-line computation to be done centrally at the ground station(including real-time simulation) by using distributed processors under the control of an executive computer<br>- such a system could be purchased essentially off-the-shelf at a modest cost |
| 17.12 | Total System S/C, G/S, Procedures Operability | - lack of experienced 3-axis stabilized S/C systems/operations personnel<br>- lack of interactive planning between system staff and S/C, G/S hardware design staff during the preliminary and detailed design phases<br>- lack of operations/operability input into detailed hardware and software design | - several subsystems or operations i.e., thermal, power batteries, eclipse, attitude re-acquisition were very difficult to manage<br>- qualification limits on several variables were occasionally or systematicaly exceeded, increasing the likelihood of component or subsystem failure | On-orbit | - trained or experienced systems/operations personnel should have early and continuous input/interaction with hardware/software designers |

SUBSYSTEM: # 17 - SYSTEMS PLANNING, TEST AND ANALYSES

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENOATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 17.13 | Real Time Simulation (RTS) Capability | - not included in preliminary planning<br>- developed by subcontractor only for attitude acquisition dynamics analysis<br>- implemented on an ad hoc basis on ≤9<br>- systems personnel did not initially appreciate potential benefits of RTS for:<br>1) Ground station hardware/software debugging<br>2) Personnel training<br>3) Spacecraft test<br>4) DOP development<br>5) NSP development | - RTS generally unavailable to operations staff until after launch<br>- RTS exceeded the ≤9 capabilities<br>- RTS had to be scheduled second/third shifts bumping all other users.<br>- initial on-orbit OOP's, NSP's would have been more complete and useful if developed using RTS | mission | - a RTS of the S/C is an invaluable systems tool for the reasons stated<br>- it is highly recommended that RTS planning start at an early stage and initial versions be ready by the S/C test and ground station implementation phase.<br>- a modern RTS facility (such as already exists at CRC/OFL) be used to implement the S/C simulation, if first shift priority can be negotiated - OR -<br>- an expanded ground station capability (see 17.11) would be capable of implementing a RTS<br>- very preliminary RTS versions would be invaluabe in subsystem design and thermal-vacuum test at the OFL. |

SUBSYSTEM: #17 - SYSTEMS PLANNING, TEST AND ANALYSIS

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 17.14 | S/C Data Reduction and Display Capability | - not included in preliminary planning<br>- no co-ordinated requirements for all potential users<br>- implemented on an ad hoc basis on $\Sigma$ 9<br>- g/s had no data playback capability other than 7 T analog tapes<br>- no planning for a central data base accessible to all users<br>- no faster than real time playback capability for analysis or s/c emergencies<br>- several duplicate development programs TEODPS, CALHIST for data display<br>- lack of truly redundant encoder data | - turnaround on historical data display ranged from 2 to 7 days<br>- relative data inaccessibility hindered normal housekeeping analysis and scheduling<br>- large amount of duty controllers' time spent hand plotting data for analysts. | mission | - see recommendations 17.11<br>- it is recommended that data base management and display planning start at an early stage and be included in an expanded ground station system<br>- a faster than real time hardcopy/plot playback capability should be a requirement<br>- an adequate graphics display for controller/analyst training should be incorporated |
| 17.15 | S/C Real Time Graphics Capability | - no spacecraft subsystem or dynamics graphics capability | - very difficult to determine subsystem state or visualize S/C attitude during operations<br>- some attitude reacquisitions took over 12 hours due to inability to visualize S/C attitude | mission | - see recommendations 17.11<br>- include modern graphics display features in future expanded ground station system<br>- include graphics in DOP's, NSP's and operator training. |

SUBSYSTEM: #17 - SYSTEMS PLANNING, TEST AND ANALYSIS

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 17.16 | S/C Test Computer Hardware/Software | - lack of early and sufficient planning<br>- PDP-8 used generally inadequate for task<br>- core limited<br>- too slow<br>- duplicate development programs (PDP-8, HP2100) to process TT&C commands/data | - entensive and expensive non-standard OS executive development required<br>- techniques and program development not made available to systems operations staff<br>- inadequate computers and programs for S/C test<br>- data only available in RAW octal format<br>- data unusable for operator training<br>- visibility of S/C performance during test decreased | test | - see recommendations 17.11<br>- develop TT&C I/O handler routines only once<br>- if S/C tested at DFL use expanded ground station system to monitor, test<br>- use RTS where practical to aid test<br>- if S/C needs remote computing capability (i.e. launch site) down load a subset of ground station developed program onto a smaller but adequate test computer |
| 17.17 | S/C Controllability Analysis and Planning | - inadequate trade-off studies to determine what control features should be automatic on-board versus automatic on-the-ground versus non-automatic with operator guided by DOP/NSP<br>- the above is very difficult to assess without previous experience and a systems/operations viewpoint | - thermal control extremely difficult/complex due to lack of thermostatic control<br>- attitude control compromised by on-board RCA/DDA ACEA not being programmable to change parameters<br>- ultimately S/C lost because automatic AFP/NESA-A action could not be inhibited. | mission | - at the preliminary design phase experienced S/C design/operations personnel should assess Mission Requirements with a view to automatic versus manual control and automatic on-board versus automatic on-the-ground control<br>- operational CTS experience indicated Automatic on-board control was a mixed blessing. |

SUBSYSTEM: #17 - SYSTEMS PLANNING, TEST AND ANALYSES

| UOE/ SCA | SHSPS | PROBLEM: DESCRIPTION | PROBLEM: CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 17.17 | S/C Controllability Analysis and Planning (Cont.) | - lack of planning as to the control consequences of losing telemetry | - automatic power switching, features (UVS, HVS) which were inappropriate and not capable of being inhibited | mission | - operational CTS experience indicated that automatic on-the-ground control was virtually impossible without truly secure and redundant telemetry<br>- with truly secure telemetry however, it is conceivable to remove space certified hardware from the S/C and perform the function on the g/s computing system; this would allow relative flexibility in changing automatic control policy/modes based on operational experience or changed Mission Requirements<br>- any automatic control mode must have a back-up manual procedural control mode i.e. attitude acquisition/ reacquisition, in experimental S/C<br>- all prime/back-up manual control modes must be planned, documented (DOP/NSP) and verified using RTS/ Ground Station emulations |

SUBSYSTEM: # 17- SYSTEMS PLANNING, TEST AND ANALYSIS

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 17.18 | S/C System Specification | - system design followed or paralleled sub-system design<br>- lack of timely system/sub system schematic functional drawings | - interface design made more difficult<br>- configuration control delayed<br>- test planning not complete | Design-Test | - spacecraft sub-system design should proceed from an overall S/C system specification which clearly defines primary requirements and constraints<br>- detailed system and sub-system schematic diagrams should be prepared and updated constantly as the project proceeds rather than initiated late in the project |
| 17.19 | Operations Scheduling | - multi-stage<br>- various groups shared responsibility | - lack of continuity<br>- complicated and delayed scheduling<br>- difficult to respond to changes | On-Orbit | - one group should be responsible for all schedule preparations with inputs directly from various sources |

SUBSYSTEM: #.17 - SYSTEMS PLANNING, TEST AND ANALYSIS

| UOE/ SCA | SHSPS | PROBLEM | | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| | | DESCRIPTION | CONSEQUENCES | | |
| 17.20 | S/C Housekeeping Operations Manpower Requirements | - lack of long range planning<br>- introduction of operations not originally planned<br>- reliance on "as and when" required consultants<br>- planned reduction of manpower with satellite age<br>- essentially a three person loading by the last year of operations | - generally insufficient manpower over on-orbit phase causing overwork and fatique<br>- proper day to day analysis not possible<br>- difficulty in manpower continuity and replacement<br>- trend analyses and prediction not generally possible<br>- DOP/NSP's not adequately updated to reflect operating experience | On-Orbit | - long range planning by experienced personnel is required in the future<br>- for experimental satellites the work load increases as the S/C ages<br>- operational experience showed that unscheduled "as and when" consultants did not work well; when needed they had other obligations and swiftly became out of date<br>- scheduled, mission-duration part-time consultants worked well for their areas of expertise<br>- if additional operations are introduced later in the Mission there must also be provisions for sufficient manpower<br>- avoid operations/schedules that result in personnel losing sleep for several consecutive days |

SUBSYSTEM: #18 OFF-LINE COMPUTING HARDWARE/SOFTWARE

| UOE/ SCA | SHSPS | PROBLEM DESCRIPTION | PROBLEM CONSEQUENCES | OIP | COMMENTS/RECOMMENDATIONS |
|---|---|---|---|---|---|
| 18.1 | SIGMA 9 General Capability | - general purpose, older, batch mode computer<br>- available to entire CRC/DOC for general scientific and accounting purposes<br>- relatively slow<br>- core limited<br>- I/O bound<br>- not designed for realtime, interactive use<br>- not operated for dedicated user utilization | - see Table 1 for a list of all Mission uses<br>- overly difficult scheduling and I/O resource allocation problems<br>- relatively long turn around for large but necessary jobs i.e. Orbit Determination and Events Prediction t/a - 48 hours,S/C data reduction and plotting capability (TEODPS, CALHIST) t/a - 48-72 hours<br>- requirement to do large jobs during second and third shifts<br>- Real Time Simulation (RTS) exceeded the capability of the computer<br>- RTS had to be scheduled second/third shift bumping all other users | On-Orbit | - see recommendations 17.11<br>- eliminate the need of mechanical data transfer between computers<br>- data retrieval, storage and display facilities should be contiguous to the ground station for ease of access by operations/analysis personnel<br>- non-realtime analysis capability would ideally be provided by a gound station dedicated computer<br>- RTS capability should be dedicated (or first shift priority) and electronically connected with the ground station on-line computing system |
| 18.2 | SIGMA 9 paper tape I/O | - difficult to punch paper tapes<br>- very slow turnaround | - difficulty in transfering Σ 9 computed data to HP2100 | 1,16 | - eliminate need of inter-computer communication<br>- provide dedicated I/O capability |