[redacted]

N73 25873

NASA CR-132256

Contract NAS1-11701

Final Report

Study of Application of Adaptive Systems to the Exploration of the Solar System

CASE FILE COPY

March 1973

Volume I Summary

MCR 73-21

Contract NAS1-11711

STUDY OF APPLICATION OF ADAPTIVE SYSTEMS TO THE EXPLORATION OF THE SOLAR SYSTEM

FINAL REPORT

Volume I

Summary

Approved

Robert B Blizard

Robert B. Blizard
Technical Director

William T Scofield

William T. Scofield
Program Manager

MARTIN MARIETTA AEROSPACE
DENVER DIVISION
Denver, Colorado 80201

FOREWORD

This is the final report on Study of Application of Adaptive Systems to the Exploration of the Solar System, performed by Martin Marietta Aerospace.

This study was performed for the Langley Research Center, NASA, under Contract NAS1-11711 between June 23, 1972 and June 8, 1973. Mr. W. Frank Staylor of the Langley Research Center was the Technical Representative of the Contracting Officer. The contract was sponsored by Planetary Programs in the Office of Space Sciences (OSS) at NASA Headquarters.

This Final Report consists of three volumes:

Volume I - Summary

Volume II - Survey of Solar System Missions

Volume III - Mars Landed Systems

ACKNOWLEDGEMENT

Martin Marietta takes pleasure in acknowledging the contributions of the following NASA personnel.

W. Frank Staylor, Technical Representative of the Contracting Officer, monitored the contract, guided the Contractor in apportioning resources to the various lines of investigation, and contributed ideas for adaptive techniques.

Edwin F. Harrison of the Langley Research Center played a large role in formulating the scope of the study and setting the ground rules for the Mars landed systems.

Paul Tarver of NASA Headquarters was one of the early supporters of the idea of adaptive systems and was instrumental in initiating the study.

CONTRIBUTORS

W. T. Scofield	Program Manager
R. B. Blizard	Technical Director
R. W. Stoffel	Computer and Software Studies
W. H. Tobey C. E. Farrell N. M. Phillips D. M. Adams	Rover studies. Mechanical systems and configurations for Mars landers.
B. C. Clark J. F. Vandrey	Science
T. W. Locke	Mission Analysis and Design
O. O. Ohlsson N. M. Phillips R. W. Stafford T. Buna A. A. Sorensen	System and subsystem studies. Structures, communications, thermal control, and power.
E. R. Cody	Cost and Schedule Studies

In addition to the above, the following people (listed in alphabetical order) contributed valuable ideas and guidance.

F. Bartko
B. A. Claussen
W. S. Cook
J. S. Derr
P. V. Fennessey
C. F. French
J. Gliozzi
H. D. Greyber
G. R. Hollenbeck
K. W. Ledbetter
J. P. Martin
R. D. Moog
W. O. Nobles
J. H. Romig
H. N. Zeiner

CONTENTS OF VOLUME I

Page

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

Over recent years there has developed an exciting field of technology aimed at simulating human intelligence with machines. This work has progressed from early feedback and control theory to sophisticated concepts of machines that can learn, think, and make decisions in strikingly human ways.

The purpose of the present study has been to examine the field of artificial intelligence to identify practical applications to unmanned spacecraft used to explore the solar system in the decade of the 80s. If an unmanned spacecraft can be made to adjust or adapt to the environment, to make decisions about what it measures and how it uses and reports the data, it can become a much more powerful tool for the science community in unlocking the secrets of the solar system.

Within this definition of an adaptive spacecraft or system, there is a broad range of variability. In terms of sophistication, an adaptive system can be extremely simple or as complex as a chess-playing machine that learns from its mistakes. At the bottom end of the sophistication scale are controls like thermostats--"if the temperature is above X degrees, turn off the heater" or "if the seismometer output exceeds Y, increase the rate at which its output is sampled."

More complexity is required when the stimulus and response are not so simple, as in a system that can detect and photograph clouds--"search the sky with an optical sensor, and if patches of unusual brightness are detected, point a camera in that direction and make repeated pictures until the clouds disappear or until the data memory is full." A rock lying on the surface of the ground poses a more subtle problem as a target to be identified in an image because, unlike a cloud, it is generally neither uniformly darker nor lighter than the background. The problem can be simplified, however, if the point of view can be chosen so that the sun strikes from the side, making a highlight and a shadow. A program to recognize a rock under these conditions has been written and tested. It requires about 200 words of computer memory, an amount that is only a small part of the capacity of a computer such as the one on the Viking lander (18,000 words).

A different type of problem that can be solved by an adaptive system is scheduling the many possible activities that a complex system can perform. For instance, some 20 different ways of operating the imaging systems of an advanced Viking lander with rover have been identified. With various ways to use the other 20 instruments and the operation of subsystems like the rover and the communication link, there will be about 50 different operations that are competing for utilization of power, data handling capacity, and sensors. Each activity has its own set of conditions that limit it--temperature, ambient light, and wind, for instance--and some activities are mutually incompatible such as operating a sampling boom while recording seismic activity with a seismometer mounted on the lander.

Making up the schedule of operations, although tedious, could be done on Earth except that to be efficient it must take advantage of transients and discoveries. Frost on the ground, a cloud, a hazard that the rover can not negotiate, or the discovery of a rock of unusual composition will call for rescheduling to obtain maximum scientific output. Chapter VI in this volume describes an executive controller that uses a system of priorities and feasibilities for adaptive scheduling. To do the adaptive scheduling, an executive controller has been developed that can be programmed into the on-board computer. A version that controls 12 operations has been programmed and simulated.

Of the artificial intelligence concepts that are being attacked today, the upper end of the sophistication scale is represented by true learning machines which are made up of a large number of logic circuits that simulate neurons. The machines are taught by exposing them to stimuli and rewarding them for good responses and punishing them for bad ones. This type of artificial intelligence was not considered in this study because it requires both theoretical and practical breakthroughs before it can be applied. Rather than looking for ways to apply a preconceived type of artificial intelligence, the approach has been to start with the mission objectives and look for ways to make decisions and changes in mission operations, both automatically and under Earth control, that increase the value of the scientific output without sacrificing reliability or mission success.

Another dimension of variability, independent of sophistication, is autonomy, ranging from direct human control to completely automatic operation with no human intervention from the beginning of the mission to the end. Although the primary object of this study has been to examine the application of autonomous adaptive systems, it is important to determine the best mix of human and machine control. The proper degree of autonomy for a mission depends largely on the required reaction speeds, how long the active phase of the mission lasts, and how long it takes to communicate between spacecraft and Earth. For instance, a Mercury orbiter with a lifetime of 100 days has little need for autonomous adaptivity. Command from Earth will be adequate to control any changes in operation of the sensors to adapt to unexpected discoveries. At the other extreme is an outer planet probe whose primary sensing period is shorter than the time for radio waves to make the round trip to Earth. Any adaptability on this mission must be controlled by equipment on the probe or possibly on the flyby spacecraft.

There are some missions that combine long lifetimes with the need for quick reactions, and for these the efficiency of an autonomous control system can be greatly enhanced if it can be modified easily by command from Earth. A Mars lander is a good example of this type of mission. Rapid reactions are required to get pictures and other data on transient events such as clouds, small dust storms, and frost. There are other reasons for making immediate decisions rather than waiting for response from Earth--safety of subsystems and of the entire mission, efficient operation of rovers and analytical instruments, control of complex chemical and biological experiments, and the scheduling of activities as discussed above.

At the same time, the Mars mission lasts long enough to let the Earth-bound scientists increase the autonomy gradually, observe the results, and modify the autonomous control system to improve its operation. A considerable part of this study has been devoted to designing a simple control system that permits an efficient combination of human and machine control.

It has been found that great benefits can be realized with computer hardware no more complicated or extensive than what will fly on the Viking '75 lander, and there is no technical reason why the adaptive concepts that have been identified can not be used on a Viking '79 mission.

The time span covered by this study extends through the 80s and it is likely that computer hardware and programming techniques will have advanced enough by the end of that time to make many things feasible that are merely speculative at the present. It is believed, therefore, that the adaptive concepts presented in this report are practical for the near future and conservative for those that are 10 or more years away.

The study has been divided into two parts. The first is a very quick look at a large number of solar system missions extending to 1990. The objective has been to examine the benefits and feasibilities of adaptive features on these missions and to determine which missions would benefit most from further study of adaptability. Chapter II describes the missions.

The second and larger part of the study was directed to three Mars missions. The first is an improved version of the Viking lander. The others add, respectively, a small tethered rover and a medium sized rover with a range of 1 kilometer. The configurations of these missions are described in Chapter III.

Chapter IV gives some examples of how adaptive features can improve solar system missions with emphasis on the Mars missions.

The design of an adaptive Mars mission is outlined in Chapter V, and Chapter VI shows some of the simulation results.

Chapters VII and VIII cover cost analysis and future technology requirements.

II. 20 SOLAR SYSTEM MISSIONS

In defining the study requirements, the NASA Technical Representative of the Contracting Officer has divided the study into two parts.

First the contractor was directed to study a relatively large number of potential unmanned missions to bodies in the solar system. The questions to be answered were: 1) what is the role of artificial intelligence (AI) or on-board decision-making capability in each of these missions? and 2) which of the planetary missions studied stand to benefit most, in terms of value of science data returned, by the application of adaptive systems? This part of the study was to be a survey activity involving little or no conceptual design and consuming approximately 10% of the total study resources.

The second part of the study was to be focused on detailed conceptual designs of Mars lander and lander/rover missions that incorporate adaptive systems to improve the value of the scientific return.

This chapter outlines the solar system missions that were selected and gives the result of ranking them for potential benefits from adaptability.

Before adaptability could be considered, it was necessary to define the missions. Launch dates were selected and propulsion requirements were determined as shown in Table II-1.

With Shuttle as the launch vehicle, maximum spacecraft weights were figured, and then subsystem weights were estimated so that the scientific payload weight could be obtained by subtraction. Communication systems received special attention

Table II-1 Missions Treated in First Part of Study

	Science Payload, kg	Launch/ Injection System	Spacecraft Propellant	Trajectory Type	Launch Date	Trip Time, Years
Mercury Orbiter	127	Shuttle/Centaur	Space Storable	Venus#	1980	1.83
Venus Orbiter	1036	Shuttle/Centaur	Space Storable	Direct	1983	0.43
Venus Probe	200	Shuttle/Centaur	Space Storable	Direct	1983	0.43
Venus Balloon	244	Shuttle/Centaur	Space Storable	Direct	1983	0.43
Venus Lander	180	Shuttle/Centaur	Space Storable	Direct	1983	0.43
Mars Orbiter	2771	Shuttle/Centaur	Space Storable	Direct	1988	0.58
Mars Lander	600	Shuttle/Centaur	Space Storable	Direct	1988	0.58
Mars Lander/Rover	300	Shuttle/Centaur	Space Storable	Direct	1988	0.58
Halley Flyby	458	Shuttle/Centaur/ HE Burner II	Monopropellant	Direct	1984	1.17
Encke Flyby	1287	Shuttle/Centaur	Monopropellant	Direct	1980	0.22
Encke Rendezvous	415	Shuttle/Centaur	NEP	Direct	1982	1.4
Vesta Rendezvous	111	Shuttle/Centaur	Space Storable	Mars#	1986	1.69
Jupiter Orbiter	248	Shuttle/Centaur HE Burner II	Space Storable	Direct	1980	3.33
Jupiter Probe/Flyby	76/371	Shuttle/Centaur HE Burner II	Monopropellant	Mars#	1982	3.56
Saturn Orbiter	97	Shuttle/Centaur HE Burner II	Space Storable	Direct	1986	4.90
Saturn Probe/Flyby	30/165	Shuttle/Centaur HE Burner II	Monopropellant	Jupiter#	1979	3.17
Uranus Orbiter	361	Shuttle/Centaur	NEP	Direct	1982	5.80
Uranus Probe/Flyby	342/97	Shuttle/Centaur SEP	Monopropellant	Saturn#	1982	7.23
Neptune Orbiter	341	Shuttle/Centaur NEP	NEP	Direct	1982	11.6
Neptune Probe/Flyby	342/51	Shuttle/Centaur SEP	Monopropellant	Saturn, Uranus#	1982	11.6

\# Gravity Assist NEP = Nuclear Electric Propulsion SEP = Solar Electric Propulsion since the data transfer capability has a large effect on the need for on-board decision making as opposed to control from Earth.

The scientific objectives for the various missions were reviewed and lists of experiments and instruments were drawn up.

Adaptability was then considered. Contract personnel conceived of some adaptive modes and got others from scientists whom they consulted. Brainstorming sessions were also productive.

Computer requirements were estimated by programming some of the adaptive modes in reasonably complete form, by programming certain computational modules that are used in common by several adaptive modes, and by estimating other requirements by comparing their complexities with operations that had been programmed.

The next step was to take a critical look at the adaptive modes as they apply to each of the missions. The questions asked were "Does this mode significantly enhance the scientific output?" and "Is it necessary or desirable to use on-board AI?"

The missions were then ranked in order of applicability of on-board AI as shown in Table II-2. Mercury and asteroid rendezvous missions ranked lowest because one expects few rapid changes requiring fast adaptation, and there is plenty of time during the mission for Earth-controlled modification of the operation of the imaging and other systems (as was done with Mariner 9) to accommodate unexpected discoveries.

The highest ranking mission was the Mars lander with rover. The reason was in part the tremendous number of decisions that must be made in operating the rover. At least hazard detection (and preferably hazard avoidance) is needed to cover a reasonable amount of terrain. Many more soil and rock samples can be gathered than can be analyzed in detail. If rover control and sample screening must be done by Earth command, the scientific output is greatly reduced from what can be accomplished with modest on-board decision making capability.

Table II-2 Mission Ranking by Value of Adaptability

Mars Lander with Rover
Outer Planet Probes
Venus Lander
Venus Probe
Halley Flyby, Encke Flyby
Outer Planet Orbiters
Venus Balloon
Venus Orbiter
Encke Rendezvous
Mars Orbiter
Asteroid Rendezvous, Mercury Orbiter

III. MARS MISSIONS

This chapter describes the three concepts of Mars landed systems: an advanced lander, an advanced lander with a small rover, and an advanced lander with a medium rover. Each has a different impact on the Viking '75 lander design and different degrees of adaptability, versatility, and sophistication. Engineering aspects of each concept were evaluated in sufficient detail to characterize their adaptive functions and to assure that the concepts were reasonable extrapolations of the Viking '75 system.

A. ADVANCED LANDER

Groundrules for the advanced lander allow it to have improved sampling ability and scientific instruments compared to Viking '75 but modifications to systems not directly related to science were kept to a minimum.

Figure III-1 shows the configuration of the advanced lander that was used for this study. The instruments that are not on the Viking '75 are shaded in the drawing. The integrated geology sample magnifier is an attachment to one of the fax cameras to enable it to get a close-up view of the soil samples before they are dropped into the processor for analysis. The drill gives information on mechanical properties of the soil and delivers samples to the analytical instruments.

The planetary landing site selection system operates during descent. It uses a camera to detect regions on the surface that show large contrast (which are likely to be rough and dangerous) and guides the lander away from these areas. Not shown in the figure are a wet chemistry experiment that detects optically

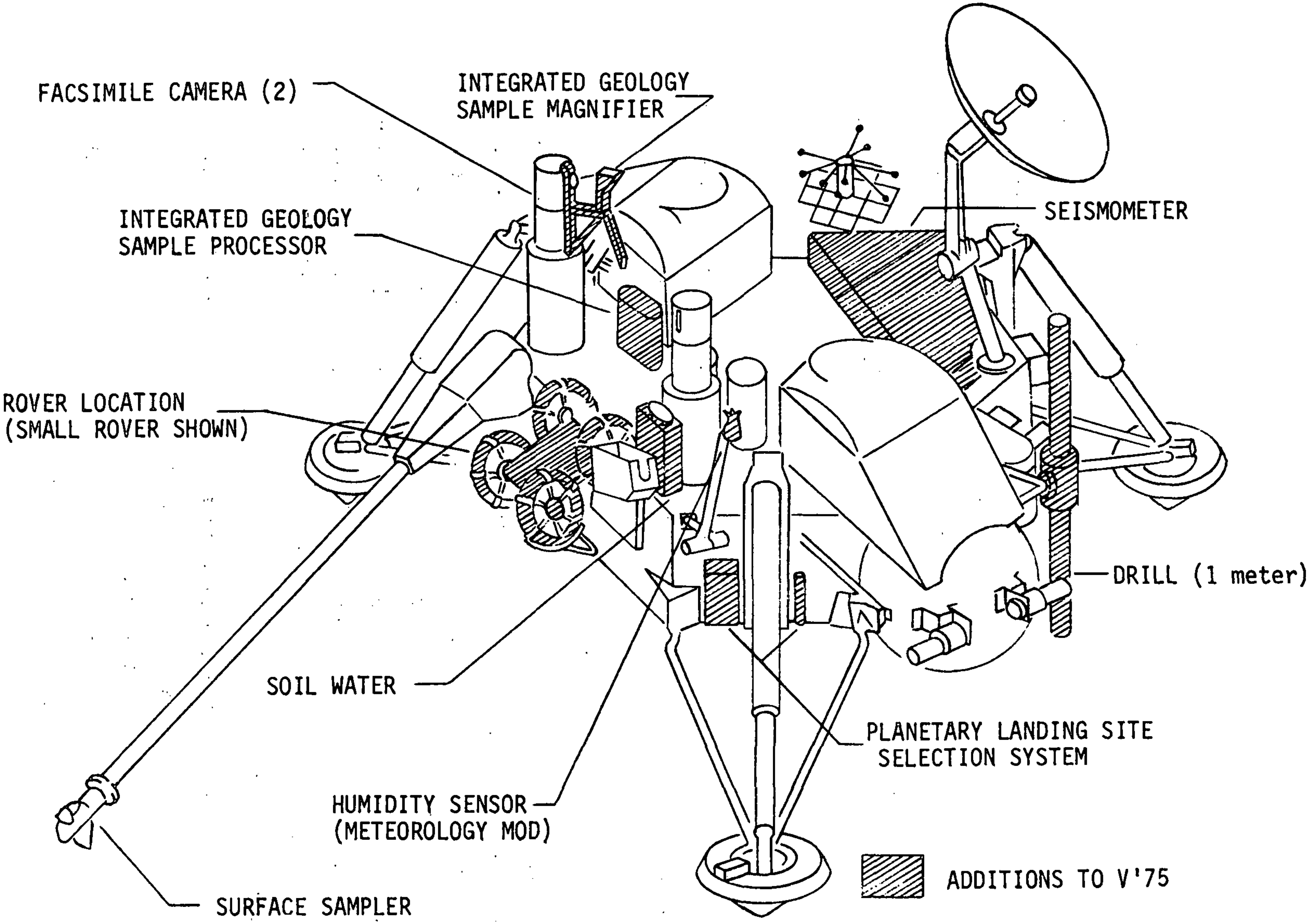

Figure III-1 Advanced Lander Concept

active amino acids and a life detection system (the experiment of B. Kok) that monitors the gas over a soil sample for changes in composition that indicate metabolism.

If a rover is added, it will be carried in available space as shown.

Table III-1 shows the mass breakdown for the advanced lander compared to the Viking '75 lander. The increase is 43 kg.

Table III-1 Advanced Lander System Mass

Subsystem	Current Viking '75	Δ Wt	Advanced Lander
Structures	106.6	+ 8.6	115.2
Propulsion	49.9		49.9
Pyro	11.8		11.8
T/C	28.1	+ 0.9	29.0
Power	98.4		98.4
Telemetry	19.5		19.5
G&C	62.7	+ 2.3	65.0
Comm	34.0		34.0
Harness	24.9	+ 4.5	29.4
Science	86.2	+26.4	112.6
Reserve	27.1		27.1
Res. Prop.	16.8		16.8
Press.	9.5		9.5
Landed Weight	575.5	+42.7	618.2 kg

B. LANDER WITH SMALL ROVER

The primary function of the small rover is to gather interesting surface samples and transport them to the lander for detailed analysis by the lander's instruments.

Martin Marietta has been investigating a small rover concept for over two years. Started under the Viking program, it was later developed to the functional model shown in Figure III-2.

A wide range of capabilities can be incorporated into a small rover. For this reason, two small rover concepts were defined. The first, illustrated in Figure III-3, can gather samples within a 100 meter radius of the lander and adds 24 kg to the 618 kg mass of the advanced lander. It receives its power and commands via a cable from the lander. It can pick up samples, make a preliminary analysis with its x-ray fluorescence spectrometer, reject samples that are just like ones already collected, and return the interesting samples to the lander for detailed analysis.

The deluxe rover has additional equipment as shown in Figure III-4. It adds 35 kg to the advanced lander.

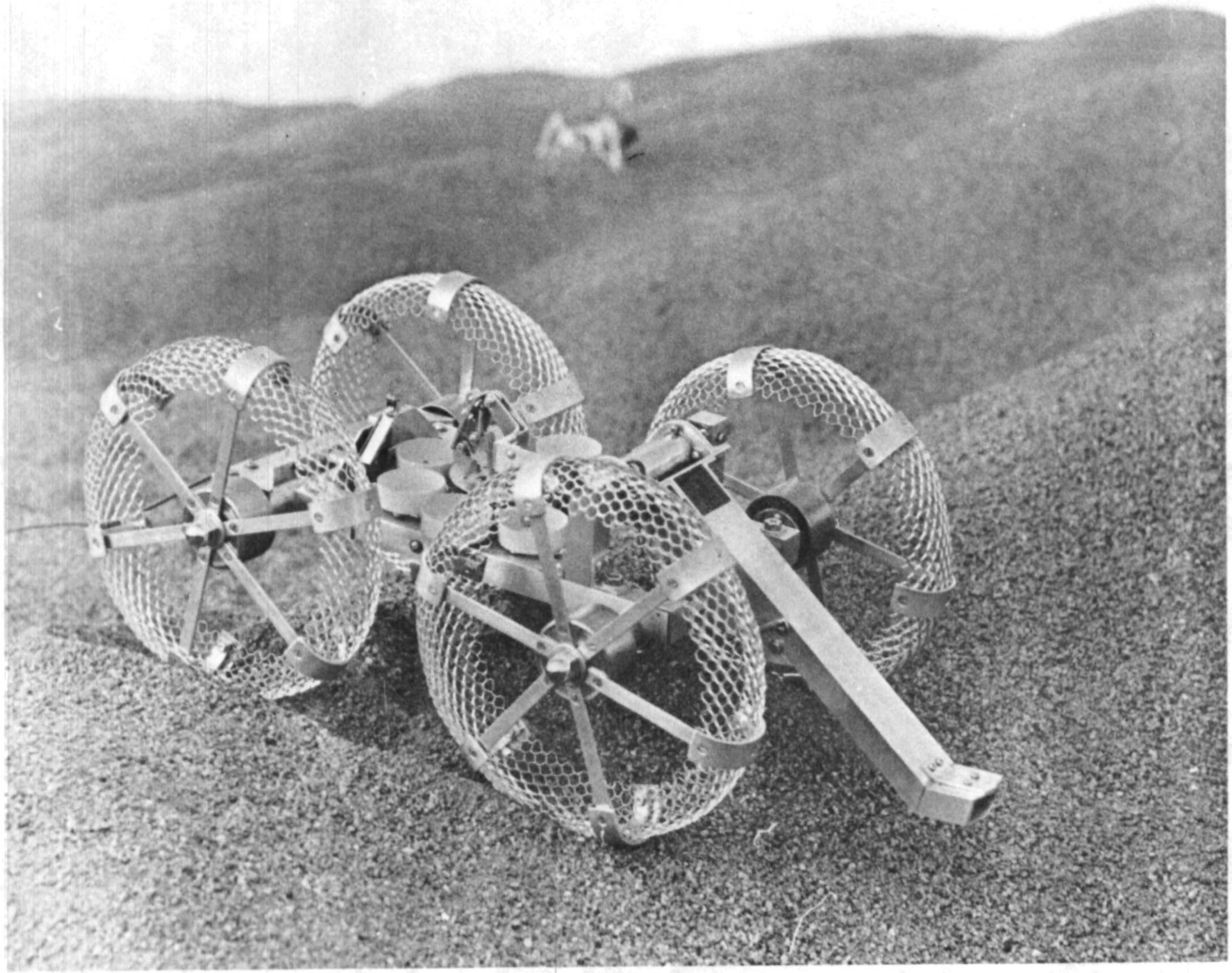

Figure III-2 Small Rover

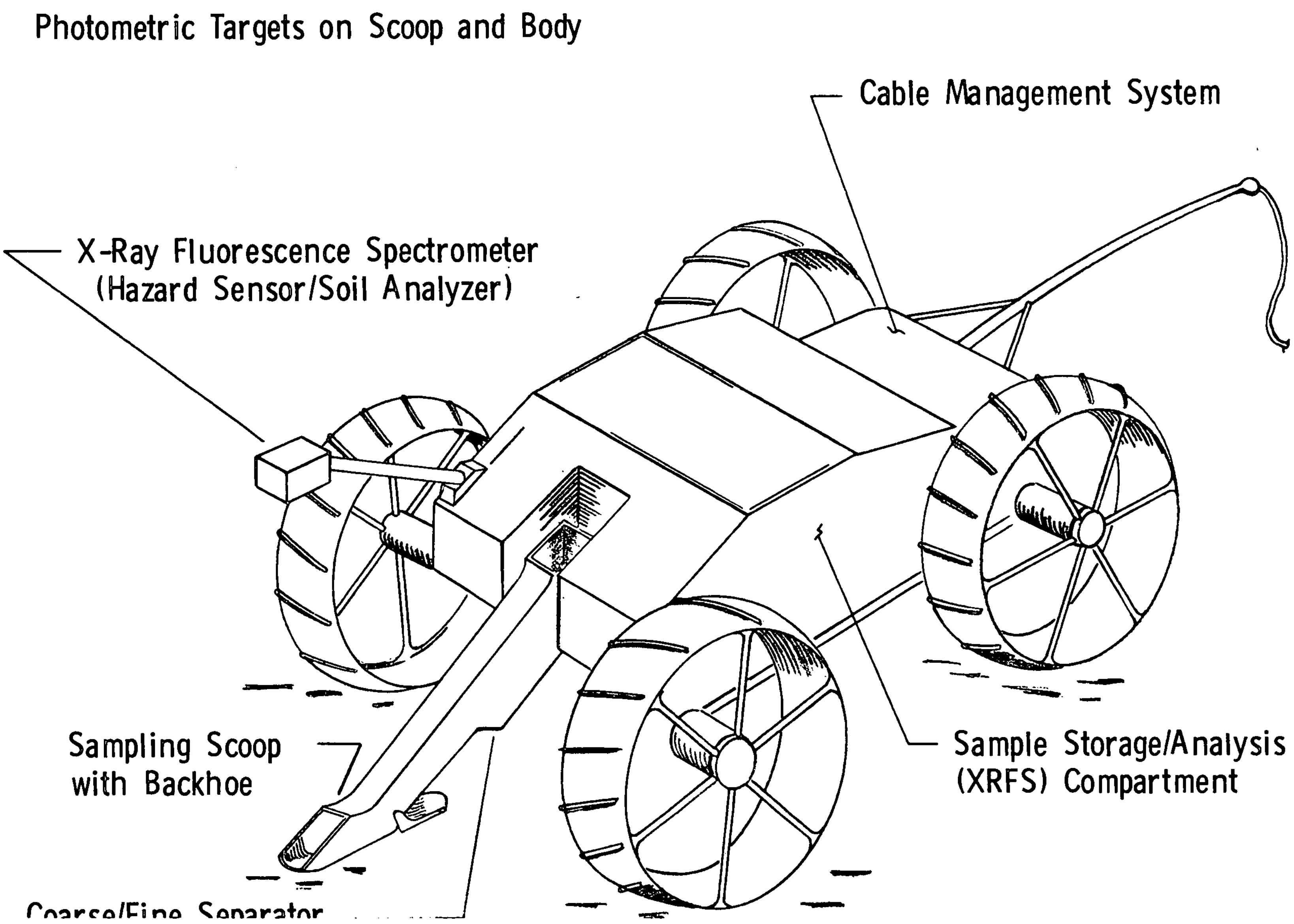

Figure III-3 Standard Small Rover

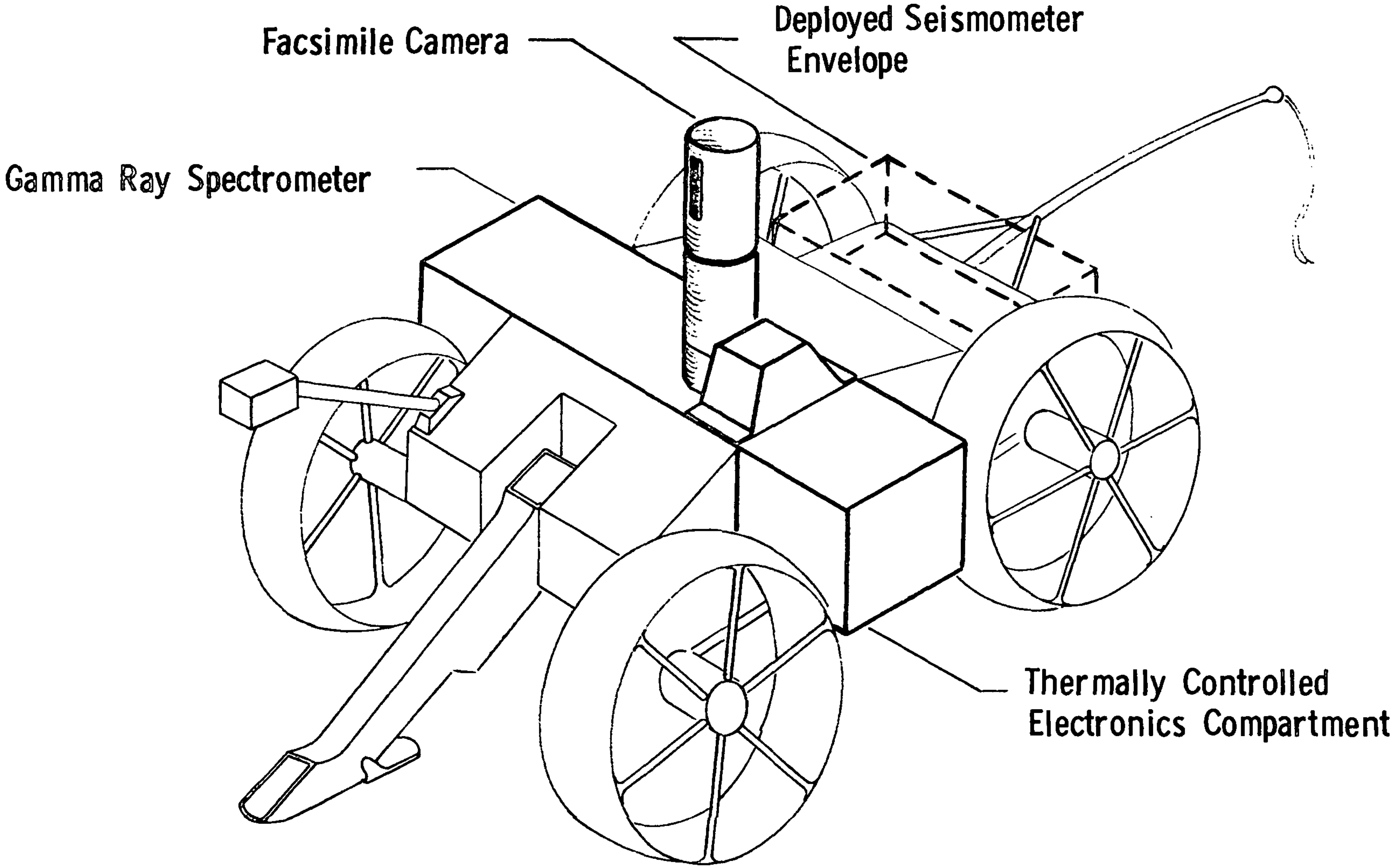

Figure III-4 Deluxe Small Rover

C. ADVANCED LANDER WITH MEDIUM ROVER

The medium rover can explore to a distance of 1 km from the lander, carries more scientific equipment than the small rover, and has enough built-in intelligence for navigation, hazard avoidance, and simple scientific decisions. More extensive lander modifications are required than with the small rover, but the essential character of the Viking '75 lander can be preserved.

Figure III-5 shows four of the candidate configurations that were considered. Each of these could be equipped with the representative science payload shown in Table III-2. The stereo imagery would use facsimile cameras approximately half the size of those on Viking '75. The "sieves" would provide initial screening of samples for inorganic and organic content. Samplers as shown would be a half size Viking '75 sampler and a 1 m rotary-percussive drill. Mechanisms for storing samples and transferring them to the lander complete this payload.

Table III-2 Medium Rover Science

Stereo Imagery - Normal, Telephoto, Quasi-Microscope

Sieves - Inorganic, Organic

Samplers - Scoop, Drill

Sample Storage and Transfer

Instruments That Could Be Deployed Away From Lander By Rover

- Active and/or Passive Seismometry Elements
- Gamma Ray Spectrometer
- Neutron Activator

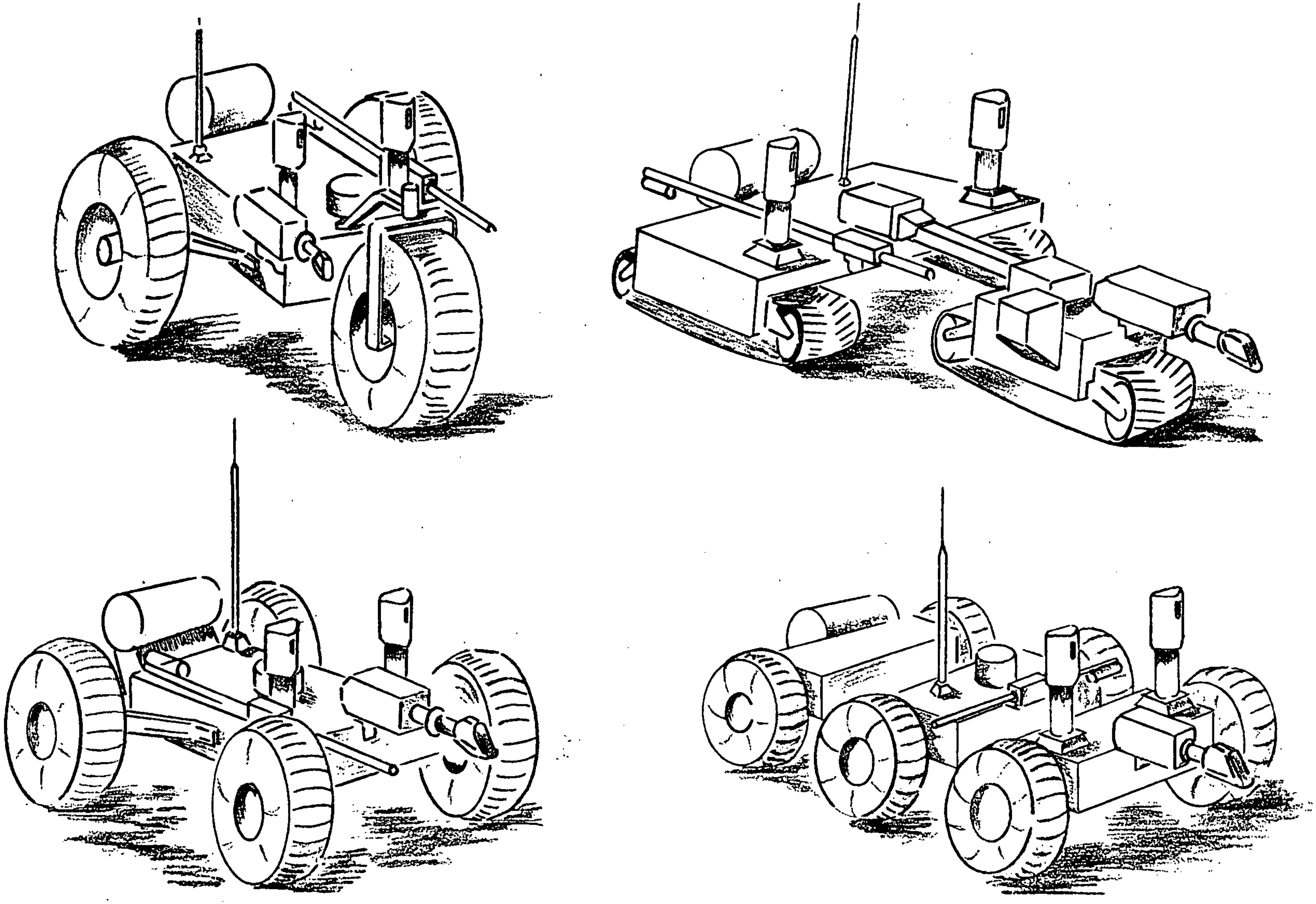

Figure III-5 Medium Rover Concepts

IV. ADAPTIVE REACTIONS

When adaptive systems are discussed, a typical reaction is to be skeptical of the ability of a computer to make scientific decisions and a concern that by attempting to make a smart system we may get one that makes bad decisions and ends up with less good data than would have been obtained with a preprogrammed set of actions. The goal of this study has not been to put scientific judgement into a computer, but rather to give the scientists a tool that enables them to automate some simple decisions so that they can be made on the lander or rover and carried out promptly enough to do some good. A first principle, then, is to put the adaptive system as directly as possible under the control of the scientific teams and to make modifications easy and fast.

A second principle that should be followed on any mission of long enough duration is to start with a minimum of autonomy and increase it as confidence is gained. For a Mars lander with rover, typical action the first day or two after landing will include exercising systems to verify their condition. The rover will be deployed and traction will be measured on the Martian soil. At this stage few decisions are made on Mars.

As confidence increases, more decisions will be made by the on-board controller. The fixed schedule of actions and measurements will be replaced by a flexible one based on priorities. The priorities will be determined in part by the observations so that recording of transients and unusual phenomena will replace less valuable activities.

Toward the end of the mission, the region close to the lander will have been thoroughly explored, and the rover may be sent on long excursions, even out of communication range, since the chance of finding something new will be worth the risk of losing the rover.

As this chapter is read, it should be kept in mind that it is not proposed to turn the lander and rover loose with a large bag of untried tricks, but rather to ease into adaptability and to tailor the criteria, thresholds, and logic according to experience and the actual conditions on the surface of the planet.

If the system is designed with flexibility, great advances in adaptability can be made in a single mission, but if it is attempted to foresee exactly how the system should react a long series of missions will be required for the same progress.

Some examples of adaptive reactions that are suitable for solar system exploration are described in the following sections. Over 100 cases were identified during the study, 74 of them applicable to Mars lander and rover missions.

A. IMAGING SYSTEMS

A camera is perhaps the most versatile and powerful single sensor that can be carried into space, and it is not surprising that it appears in many of the better applications of adaptability. A typical mode of operation is to detect something of interest in the field of a relatively wide angle imager and direct the pointing of another sensor so that more detailed data can be obtained (Figure IV-1). The second sensor may be a narrow angle camera, an IR or UV radiometer, or a sampling boom on a rover.

For vehicles orbiting or passing cloudy planets, interesting targets will include spots, clouds of unusual color, storms, and boundaries between cloud types. An interesting variation is detecting features on the daylight side and investigating them with an IR sensor when they reach the dark side (Figure IV-2). Alternatively, an IR map of the dark side can be analyzed to detect anomalies, and these can be examined with high resolution imaging when they pass into daylight.

Programs to identify features in images can be simple or complex depending on the subtlety of the discrimination criteria. Finding the darkest or brightest pixel (picture element) requires only a few words of instruction. A next step in selectivity is to put limits on the size of a bright or dark spot. A program that finds objects with brightness, length, and width between specified limits can be written with 132 words.

A program that recognizes shadow-casting objects, such as a rock on a smooth surface, has limits on size and brightness of both the shadow and the highlight. About 200 words are needed for the routine described in a Martin Marietta report.*

---

* Keith H. Hill and Robert B. Blizard: *A Rock Finder Program for Adaptive Planetary Surface Experiments*. Martin Marietta Report D-72-48739-001, October 1972.

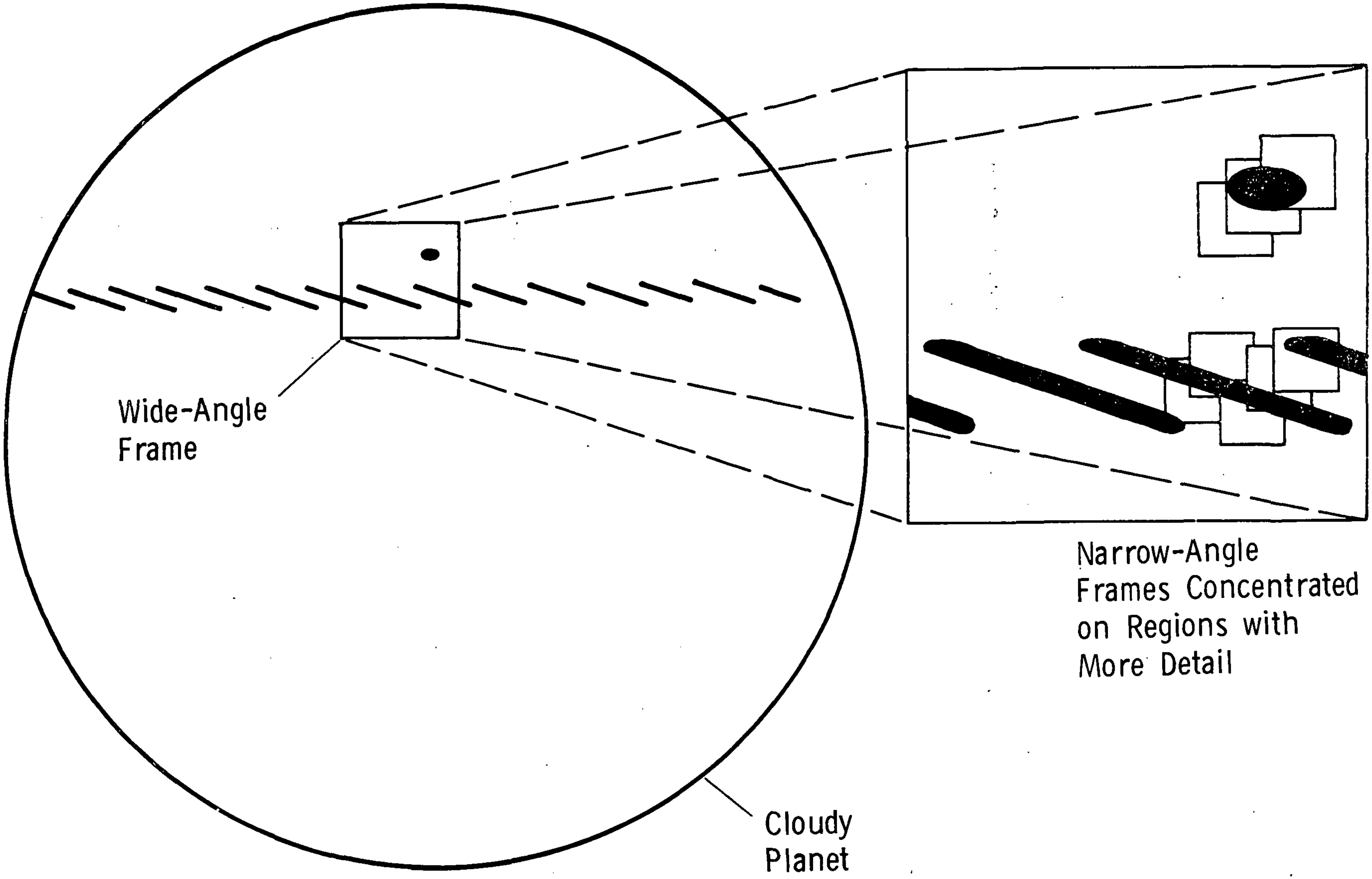

Figure IV-1 Planetary Orbiter--Capturing Detail on a Fast Periapsis Pass

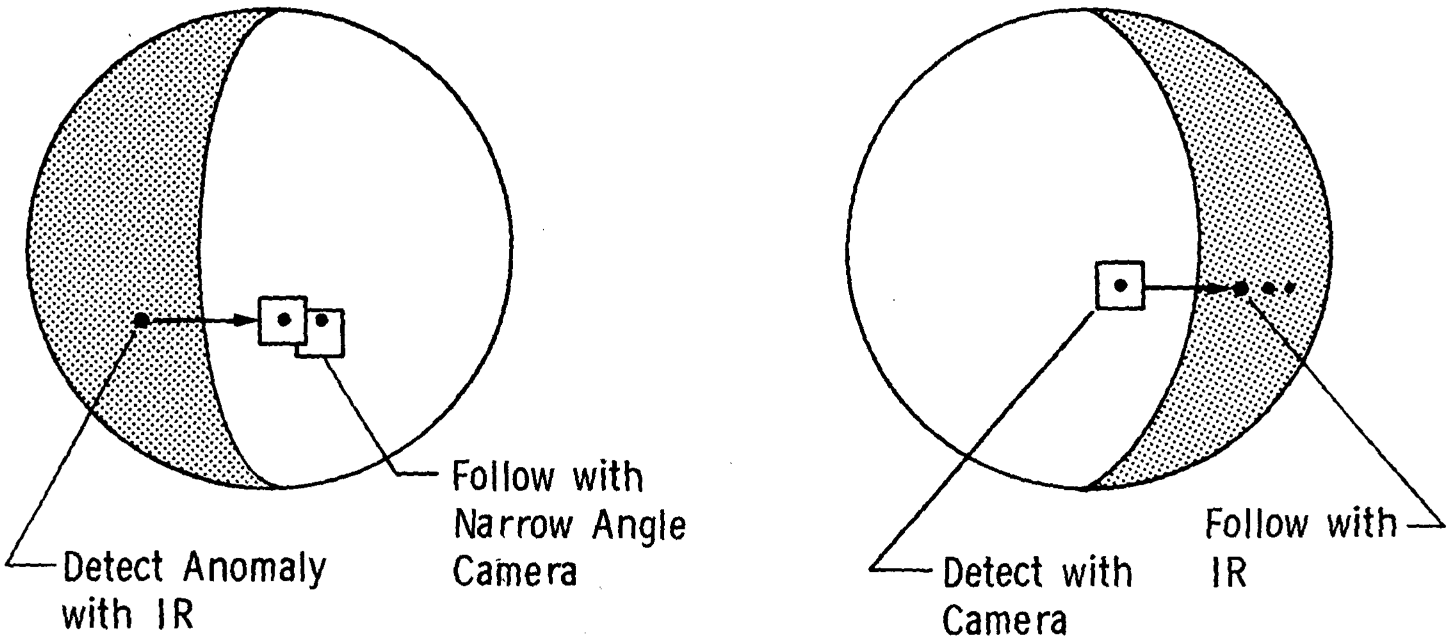

Figure IV-2 Planetary Orbiter--Adaptive Use of Two Sensors

An imaging system is a powerful tool for detecting changes. The Mars lander fax cameras can scan the sky and terrain rapidly taking data only at discrete points separated by a few degrees of angle as shown in Figure IV-3. Cloud searches will be easy to do at frequent intervals through the day since the clouds can be detected by their brightness contrast with surrounding regions. When a cloud has been found, a series of pictures can be made to show growth, decay, and movement caused by wind. The rover camera can be used simultaneously to get long-base stereo pictures so that range can be determined. A non-adaptive lander could only record clouds as rare chance occurrences in a large number of otherwise uninteresting pictures of the sky.

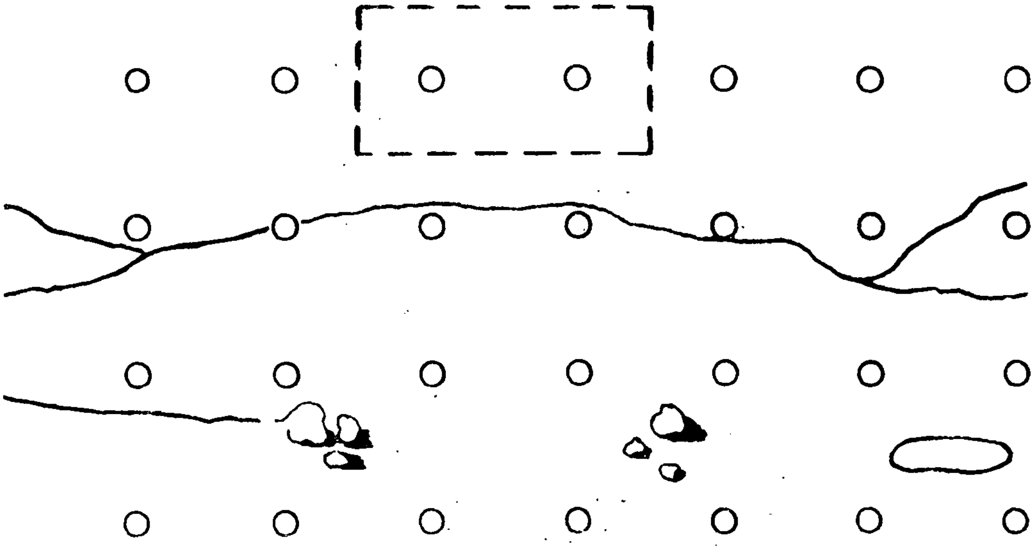

Figure IV-3 Using an Imaging System to Search for Changes

If changes in the sky are interesting, changes on the ground are even more so. They may be caused by frost, aeolian deposits or removals, slides, or vegetative growth. These changes can be detected by the camera in a way similar to that used for finding clouds. For surface changes, however, it will be necessary to compare the brightness signal along the search line point by point to the signal obtained the day before with the same Sun angle. The amount of memory required to store yesterday's data will not be large if, say, a thousand points are recorded, which should give adequate coverage.

There are many other adaptive ways to operate the cameras. When the wind gets strong, the camera windows should be turned behind the protective posts to keep them from being abraded or coated with dust. When a rover is making sorties, its camera can be used to make pictures at regular distance intervals to record the undisturbed terrain, and when it runs into difficulty, both lander and rover cameras should make pictures of its situation to help the team on Earth decide what to do.

B. BIOLOGICAL ASSAY

The life detection experiment proposed for the advanced lander is the method of B. Kok and is shown schematically in Figure IV-4. Soil samples are held in small vessels (although the experiment can also be done in situ with a bell over the ground) and the changes in gas composition are monitored with a mass spectrometer. Nutrients may be added and temperature may be controlled.

Presence of life is judged by examining the dynamics of the changes in amounts of gases with mass numbers up to 50 or 60. The total volume of gas over each sample is kept small to increase the sensitivity to changes, and a large number of gas samples must be taken to determine the form of the variations in time. Efficient use of the gas is thus important to success of the experiment.

A malfunction of a sampling valve could be catastrophic since it would soon bleed off the gas from the test cell. Corrective action from Earth would be much too late to do any good, but onboard detection of failure to shut off could trigger a cycling of the valve to attempt to get rid of a particle in the seat, and if that fails a back-up valve can be closed. The benefit of adaptability can be realized in reduced cost by substituting software for extremely expensive development and qualification of ultra-reliable valves.

The distinction between ordinary chemical reactions and those mediated by living organisms will be based on the rates and shapes of their variations with time. Some reactions will be slow. Others will go rapidly at first and then stop. Organisms that are dormant may show no activity for many days and then metabolize rapidly after awakening. Figure IV-5 shows some of the types of curves that have been obtained with terrestrial soil. Choosing the

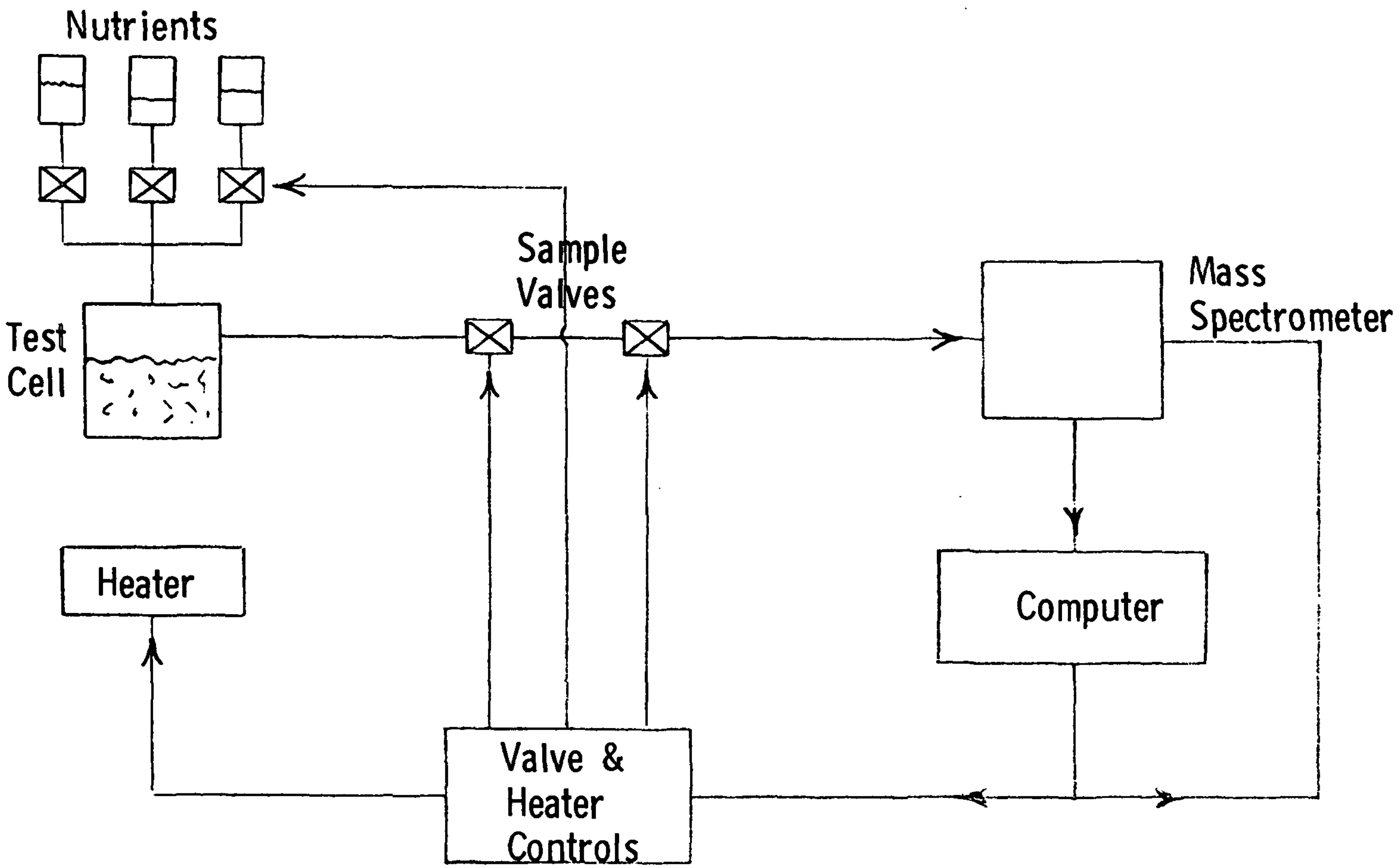

Figure IV-4 Adaptive Biological Assay

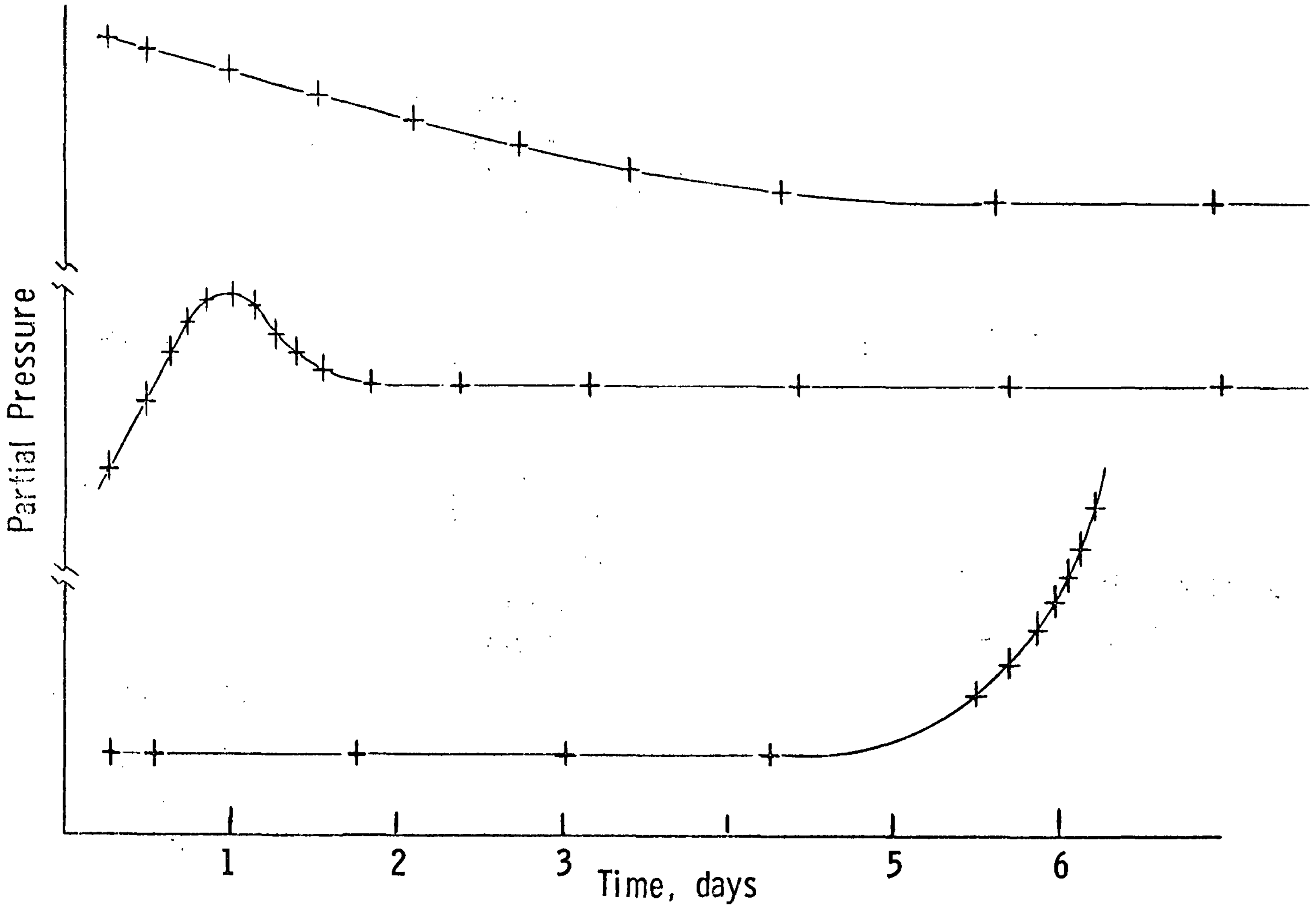

Figure IV-5 Adaptive Sampling Rate for Biological Assay frequency for sampling the gas is difficult. It it is too long the sudden changes will not be recorded in detail, and if the gas is sampled too often it may all be used up before the action starts.

The dilemma is solved by taking the next sample after a time that depends on the rate of change indicated by the results of the last two samples, as illustrated by the crosses in the figure. Further savings can be made in the use of the gas by controlling the counting time of the mass spectrometer to get just enough counts for good statistics. The quantitative increase in efficiency depends on the actual experimental results, but improvements of a factor of four or more seem conservative.

C. ROVERS

A major reason for having a rover is to manipulate the Martian surface and go part way toward bridging the gap between a passive observer and a geologist on the scene with hands, feet, and hammer.

An adaptive system that uses the outputs of force and position sensors on the sampling arms and rover drives will be able to do such things as digging trenches and testing the mechanics of the soil much more efficiently than a non-adaptive system that can only be commanded in terms of wheel revolutions and specified displacements and angles for the sampling arms.

As a typical interactive task, consider how a rover would turn over a rock on the surface so that its underside can be observed. The strategy for the small rover is to drive its sampler against the rock slightly below the surface and then lift the rock and roll it over by a coordinated raising of the sampler and forward motion on the rover's wheels.

The unadaptive rover's first problem is making gentle contact with the rock. The rock should be lifted out and not pushed horizontally destroying the information in the soil beneath it. The approach must therefore be made in several approximations each of which require a one-day turn-around time if an orbiter relay is used.

When lifting starts it must be done cautiously. If the rock does not move, the rover can turn itself over with its sampler.

Coordination between forward motion and lifting will be difficult at best. The unpleasant alternatives are small incremental motions each requiring a day of elapsed time and bolder action with risk of dropping the rock. Elapsed time would be about six days.

The adaptive system has everything needed to get the job done in one day with one set of commands. Since several different actions will be commanded with one transmission, it is probably a good idea to check them out on Earth with a duplicate rover and a rock of about the same size and shape (the underground shape can only be guessed at) in similar soil, and a total of two days would be needed for the job.

D. ATMOSPHERIC PROBE

The composition of the various cloud layers believed to exist in many planetary atmospheres is of great interest. For the foreseeable future, atmospheric probes will be small and will only be able to take a few samples for analysis. To be sure of getting good coverage of the clouds, an adaptive system would detect clouds with a nephelometer and activate the sampler once in each layer.

V. ADAPTIVE CONTROL SYSTEM DESIGN

This chapter describes an adaptive control system that is suitable for a Mars lander with or without a rover. Three levels of control are used. The lowest level is concerned with the operation of individual experiments or subsystems and is embodied in software packages called "operating routines." Some of the operating routines are simple, while others are more complex and may involve adaptive features.

At the next level of control, the "executive controller" determines which routines will be active at a particular time, and therefore it decides when to perform all the scientific and engineering tasks.

At the top level are the teams of scientists and others who must be accommodated with an interface that permits them to operate with top efficiency.

Section A discusses the objectives of the system design. Section B outlines the approach and the organization. Design details are given in Volume III Chapter V and its appendixes.

A. OBJECTIVES

Consider first what characteristics are desirable in an executive controller.

1. Flexibility

The controller must be easy to modify at any time until the end of the mission. During the period before landing, scientists and others will continue to get good ideas on how to improve the adaptive system, and after landing changes will have to be made to adjust to actual conditions and discoveries. Flexibility will also make it possible to ease into autonomous operation gradually as confidence is gained.

2. Scope of Control

It is impossible to predict all the types of interactions and the modes of control that will become desirable during a mission. If the system is designed so that the computer has access to all the data generated on board, planning and software design become easier because it is not necessary to decide in advance what data will be used to control each function of the landed system.

3. Man-Machine Interface

The executive controller is the principal set of controls that will be used to make the landed system do what the scientists want, and it is important to make it easy to understand and use.

The responsibility for controlling space missions is naturally divided between scientific and mission operations teams. The scientists optimize the scientific return, and the operations team must assure the safety of the mission. The organization of the executive controller should reflect this division, and the science team should be able to change the emphasis and operation of the various scientific experiments without the risk of inadvertently jeopardizing the success of the whole mission. Elaborate cycles of approval and verification should be avoided so that the scientific decisions can be made and executed in a short time.

B. APPROACH AND ORGANIZATION

Figure V-1 shows the overall organization of an adaptive system which allows two groups of ground controllers, the science team and the mission operations group to exercise control over a single set of science and engineering hardware almost independently of each other. As can be seen from this figure, the science team's input to control is in terms of priority--"How much do we want to do this action?" The mission operations input is in terms of feasibility--"Is it safe for the total mission if this action is allowed?"

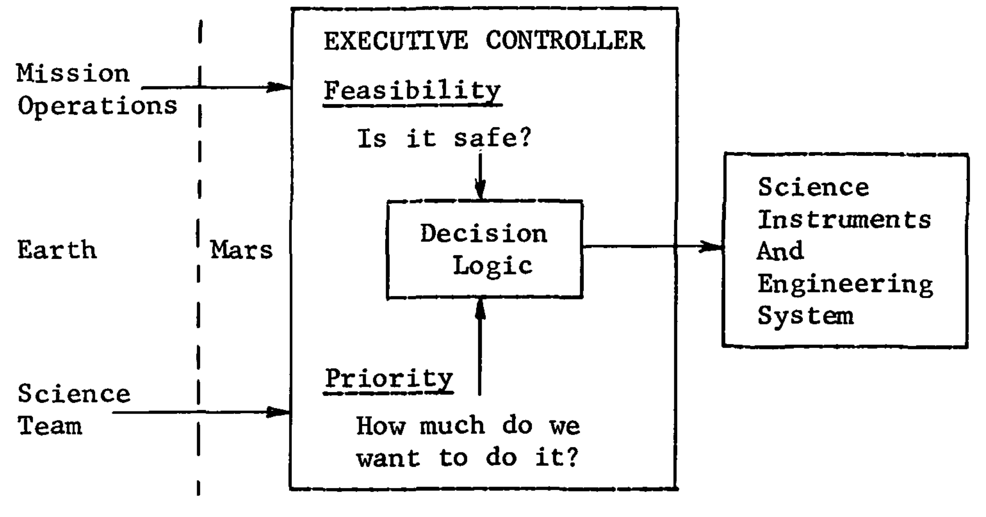

Figure V-1 Executive Controller Approach

At regular intervals the executive controller makes up a list of things to do based on priority and feasibility.

Some examples of items that are used in computing priorities are:

Continuity. An action that has been started but is not complete will get an increment in its priority proportional to the importance of not interrupting it.

Distance travelled or time elapsed since last action of a particular kind.

Interesting discovery. A change in soil type would greatly increase the priority for taking a sample.

Weather. A high wind should alter the priority equation for sampling the collector of atmospheric dust.

Time of day. A search for clouds should probably have higher priority in the afternoon.

Commands. The actions of the landed system can conveniently be controlled by issuing commands through priority changes.

Feasibility is computed as "yes" or "no". Typical items in the feasibility equations include available power, ambient and internal temperatures, wind speeds that endanger camera lenses, and hazards to a rover. If some action must be prevented, perhaps because of equipment failure, the feasibility equation can be modified from the Earth to give an unconditional "no".

Figure V-2 is a block diagram of the adaptive system developed during the contract. The several blocks on the right represent the science instruments and engineering subsystems which are the controlled hardware. With the exception of the oval which is the ground control function, the rest of the diagram blocks are the computer software.

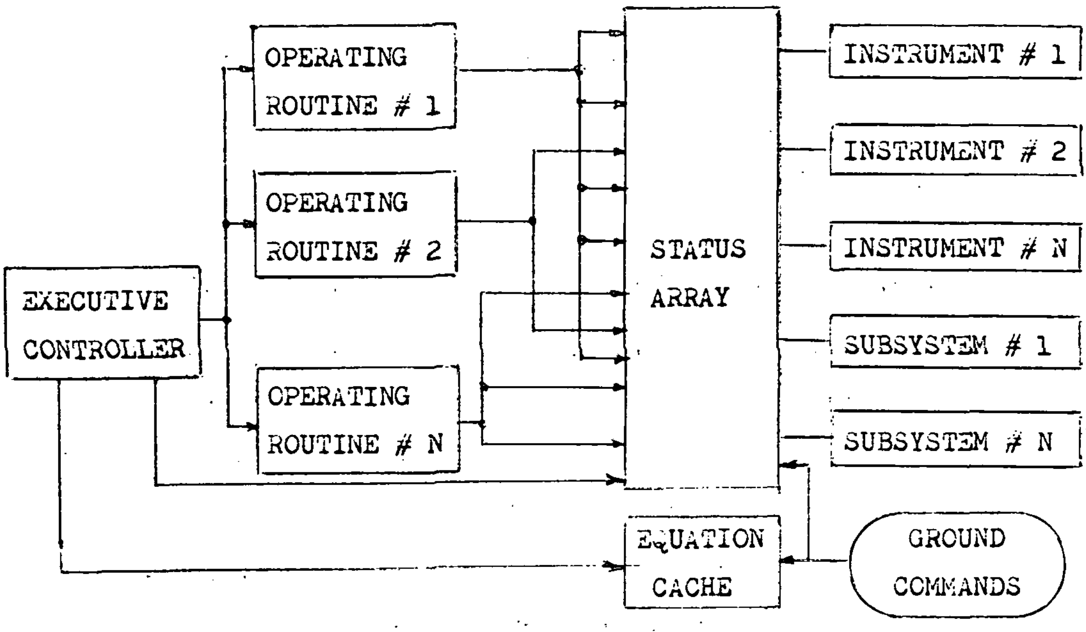

Figure V-2 Adaptive System Block Diagram

The status array, which is the storage place for numerical values provides the interface between the computer software and the spacecraft hardware. Values are placed in this array at any time by direct command and by the hardware, operating routines, and the executive controller during the mission.

The equation cache holds the priority and feasibility equations that tell how to calculate the priority and feasibility. The executive controller evaluates these equations by substituting values drawn from the status array.

The actual equations are made up of addresses in the status array for the applicable values and various codes representing a set of 12 operators that are used to combine these values. The equations are loaded prior to launch but may be easily changed by ground command during the mission.

As mentioned above, the operating routines provide the software for the control of the individual components of hardware. In general each important mode of operation of each component requires a separate operating routine.

C. COMPUTER SIZING

Table V-1 shows the estimated memory requirements for programing and data storage to accommodate the adaptive system for the Mars lander with small rover. The executive controller and some of the operating routines have been programmed in Fortran. The requirements for other routines have been estimated by comparing them to programmed routines of similar complexity. The requirements for the miscellaneous variables, equation cache, and status array are based on 43 operating routines that have been identified. The word count in the table is based on a 24-bit word, the same as used in the Viking '75 GCSC computer.

Table V-1 Computer Sizing Summary

Use	Words
Executive Controller	2810
Miscellaneous Variables	400
Equation Cache	1690
Status Array	1575
Operating Routines	
Lander	5264
Small Rover - Standard	690
Small Rover - Deluxe Additions	1238
Computational Routines	
Routine A - Sample Screening	1390
Routine B - Rock Sample Locator	200
	15257

It should be noted that the operating routines which would be required by the medium rover have not been estimated since it has been assumed that the rover will carry its own computer which should be smaller in requirements than the lander/small rover combination.

The present Viking GCSC computer memory has 20480 words of which only 18432 are available for programming use. Approximately 6000 words of this memory are being used for purposes beyond the scope of this study; for example, control of the terminal descent engines. In order to use the present concept on this computer, one of two possible actions would be necessary: 1) the adaptive programming can be stored on the tape recorder and loaded into the computer memory after landing is completed, or 2) the computer memory can be expanded toward the maximum memory addressable by the computer, 32768 words.

VI. ADAPTIVE SYSTEM SIMULATION

In order to check out the operation of the executive controller and the general system concept, a realistic portion of the operating routines which would be required by a lander and a small deluxe rover were programmed and appropriate controlling equations and status array values provided. Appendix C gives a detailed listing of these inputs and conditions. The size of the system was picked to provide an interesting, yet simple simulation.

Figure VI-1 displays the assumed configuration consisting of 12 operating routines. The instruments include a rover camera, the lander cameras, and the integrated meteorology system. In addition, rover motion and data transmission are considered. All instruments operate in more than one mode, but only in one mode at a time. Each operating mode requires a separate operating routine to facilitate switching between modes. The principal transient events which control the sequencing of these instruments are indicated. A cloud search routine, upon detecting a cloud, activates a camera mode which takes a TV view of the cloud. The seismometer and meteorology experiments can switch themselves into high data rate modes when unusual measurements are taken. The rover on detecting a hazard to its motion, signals its camera to take a panorama of its surroundings which in turn calls for a TV view of the rover from the lander camera.

Other interactions not shown include the inhibiting of the rover motion and the lander camera while the seismometer is in its high data rate mode, covering the two camera lenses when the wind exceeds a given value, stopping the rover motion when the wind exceeds another set value, inhibiting camera operation

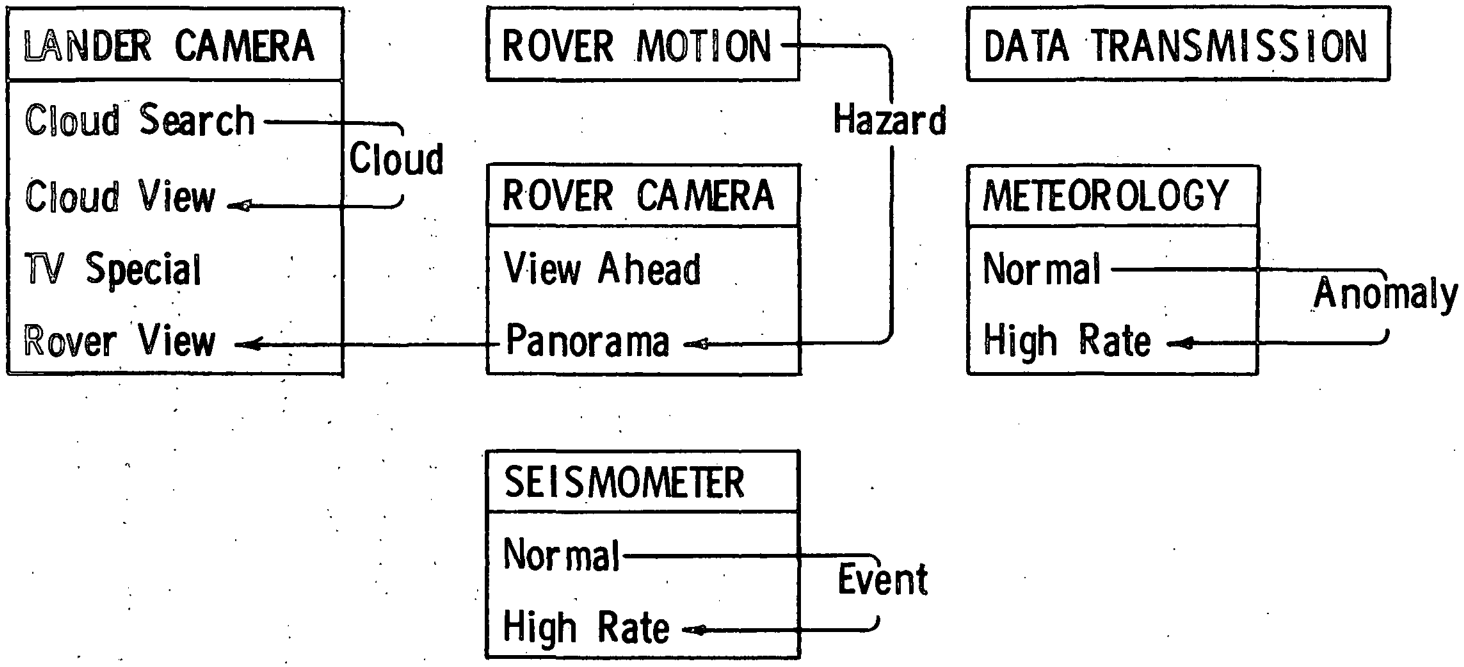

Figure VI-1 Configuration of System Simulation except by ground command during darkness, making the rover camera priorities a function of the distance the rover has travelled, and constraining the system activity within power and memory limits.

A random number generator is used to inject "events" such as hazards to the rover, weather changes, and seismic events. The following pages show some of the scenario that has been obtained in the form of computer print-out.

Each of the 12 routines is represented by a column in the print-out.

METEOROLOGY is the regular mode of gathering weather data.

The HI DATA METEOR mode is turned on when the weather is more interesting than usual. In this mode the meteorological instruments are sampled more often to record detailed dynamics of weather changes.

CLOUD SEARCH is a way of using the imaging system to make a quick check of the sky to see whether clouds are present. In the CLOUD VIEW mode the imaging system takes pictures where the clouds were detected.

ROVER VIEW is a picture of the rover taken from the lander. ROVER PANORAMA (column 9) is a 360° view from the rover camera. Both of these modes are useful in deciding how to give commands from Earth to get the rover out of trouble if the on-board system is unsuccessful.

ROVER MOTION makes the rover proceed according to stored instructions that have been provided by command from Earth.

For TV VIEW AHEAD, the rover takes a picture of the scene ahead. It looks down as steeply as possible to record the details of the ground and looks up far enough to include some local landmarks. It is normally activated at regular short distance intervals (2.5 meters as programmed here) but of course it may be delayed if more urgent (higher priority) actions are required.

SEISMOMETER and HI RATE SEISMO are the low and high data rate modes.

DATA XMISSION is the data dump to the orbiter. It normally occurs as soon as the orbiter is high enough over the horizon. Even this important action can be delayed by competing modes of operation if they have high enough priorities, although this does not happen in the following scenario.

Each page of print-out is keyed by a page of explanation.

THIS PAGE INTENTIONALLY LEFT BLANK.

SYSTEM SIMULATION - ROVER HAZARD DETECTED

In the format used to print out the condition of the simulated system, two lines of information are shown for each time period. The first lines give the time if it happens to be a multiple of five, and the priority of each of the twelve operating routines. On the second line are found asterisks below the priority of routines which are active, the total number of kilobits of data stored in the memory, the unused battery and RTG power after the time period. The time is given in minutes and the power in watts. Preceding the two lines of any time period are on occasion listings of data generated in the operating routines or commands issued by the ground during that time period.

Four routines are essentially free-running: meteorology, cloud search, rover motion, and the seismometer. Two of these routines, meteorology and seismometer, are on initially since there was no built-in delay for their operation. Since they draw 5 and 10 watts and the total RTG power is set at 42 watts, there is an excess of 27 watts shown for the first two minutes.

The following events of note occurred during the mission times shown:

1. At time = 722, rover motion is enabled with an initial priority of 10. Since power is available, the rover starts at time = 723.
2. At time = 725, excessive tension on the rover tether is detected and therefore at time = 726 the rover motion is interrupted and the rover camera starts a panorama to provide information for the ground command to determine the cause of the rover hazard.
3. At time = 731, the cloud search routine is enabled so that the priority starts its rise.

SYSTEM SIMULATION - ROVER HAZARD DETECTED

```
                 ROVER VIEW  ROVER MOTION             MEMORY     EXCESS
TIME          TV SPECIAL  ↓  ↓  TV VIEW AHEAD         STORED   BAT   RTG
           CLOUD VIEW  ↓  ↓  ↓  ↓  ROVER PANORAMA      KBIT    PWR   PWR
      CLOUD SEARCH  ↓  ↓  ↓  ↓  ↓  ↓  SEISMOMETER
 HI DATA METEOR  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  HI RATE SEISMO
 METEOROLOGY  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  DATA XMISSION
           ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓
 720      75  0  0  0  0  0  0  0  0 20  0  0
           *                          *                    0  10.0  27.0
          75  0  0  0  0  0  0  0  0 45  0  0
           *                          *                    0  10.0  27.0
          75  0  0  0  0  0 10  0  0 45  0  0
           *                 *        *                    0   7.0   0.
          75  0  0  0  0  0 40  0  0 45  0  0
           *                 *        *                    1   7.0   0.
          75  0  0  0  0  0 40  0  0 45  0  0
           *                 *        *                    2   7.0   0.
      HAZARD DETECTED -ROVER TETHER TENSION IS    .49
 725      75  0  0  0  0  0 40  0  0 45  0  0
           *                 *        *                    2   6.9   0.
          75  0  0  0  0  0 40  0 60 45  0  0
           *                       *  *                   18   9.9   8.1
          75  0  0  0  0  0 15  0 60 45  0  0
           *                       *  *                   33   9.9   8.1
          75  0  0  0  0  0 16  0 60 45  0  0
           *                       *  *                   49   9.9   8.1
          75  0  0  0  0  0 17  0 60 45  0  0
           *                       *  *                   64   9.9   8.1
 730      75  0  0  0  0  0 18  0 60 45  0  0
           *                       *  *                   79   9.9   8.1
          75  0  1  0  0  0 19  0 60 45  0  0
           *                       *  *                   95   9.9   8.1
```

SYSTEM SIMULATION - METEOROLOGY AND CLOUDS

The following events of note occurred during the mission times shown:

1. At time = 734, the seismometer experiment times out (14 minutes) which allows power to be switched to the cloud search experiment which has a priority of 5. The rover motion with a higher priority is not turned on because of the 30 watts of power required. The priority of the cloud search experiment is raised to 55 once it is on to keep it on.
2. At time = 735, the meteorology detects an anomaly such as an unusual rise in temperature and the high data rate meteorology is turned on.
3. At time = 736, the cloud search experiment detects a cloud which provides a high priority to the cloud view experiment which turns on at time = 737.
4. At time = 741, the rover camera finishes its panorama which in turn enables the lander camera to take a view in the direction of the rover.
5. At time = 742, the turn-off of the rover camera frees power to enable the seismometer to turn back on. At the same time, the lander camera finishes its picture of the cloud, which allows the camera to swing around to make a view of the rover.
6. At time = 743, the lander camera starts taking a view of the rover.

SYSTEM SIMULATION - METEOROLOGY AND CLOUD

```
                 ROVER VIEW  ROVER MOTION             MEMORY     EXCESS
TIME          TV SPECIAL  ↓  ↓  TV VIEW AHEAD         STORED   BAT   RTG
           CLOUD VIEW  ↓  ↓  ↓  ↓  ROVER PANORAMA      KBIT    PWR   PWR
      CLOUD SEARCH  ↓  ↓  ↓  ↓  ↓  ↓  SEISMOMETER
 HI DATA METEOR  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  HI RATE SEISMO
 METEOROLOGY  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  DATA XMISSION
           ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓  ↓
          75  0  2  0  0  0 20  0 60 45  0  0
           *                       *  *                  110   9.9   8.1
          75  0  3  0  0  0 21  0 60 45  0  0
           *                       *  *                  126   9.9   8.1
          75  0  4  0  0  0 22  0 60 45  0  0
           *                       *  *                  141   9.9   8.1
      METEOROLOGY ANOMALY DETECTED
 735      75  0  5  0  0  0 23  0 60 45  0  0
           *     *                 *                     172   9.1   0.
      CLOUD DETECTED
          75 80 55  0  0  0 24  0 60 20  0  0
              *  *                 *                     203   9.1   0.
           0 80 55 82  0  0 25  0 60 21  0  0
              *     *              *                    1178   9.1   0.
           0 80  8 85  0  0 26  0 60 21  0  0
              *     *              *                    2154   9.1   0.
           0 80  9 85  0  0 27  0 60 22  0  0
              *     *              *                    3129   9.1   0.
 740       0 80 10 85  0  0 28  0 60 22  0  0
              *     *              *                    4105   9.1   0.
           0 80 11 85  0  0 29  0 60 23  0  0
              *     *              *                    5080   9.1   0.
           0 80 12 85  0  0 30  0 60 23  0  0
                    *                 *                 6040   9.9  13.1
          75  0 13 85  0 70 31  0  0 45  0  0
           *              *           *                 7000   9.9   8.1
```

VII. COST AND SCHEDULE

A. ADAPTIVE MARS MISSION COSTS

Preliminary cost estimates were made for the four adaptive Mars missions described in this study. The purpose of the estimates was not so much to develop absolute total costs of the missions as to identify the additional costs required to fly adaptive missions compared with fixed sequence missions. To allow this comparison to be made most clearly, the 1979 mission was chosen as the costing baseline. This permitted cross-referencing to existing Viking '79 program estimates, and also avoided the need to mix in space storable propulsion systems which would have distorted the cost comparisons.

The following ground rules were followed in the estimates:

1. 1979 launch opportunity
2. single launch, no spare spacecraft
3. lander and orbiter costs based on Viking '79
    a. maximum inheritance from Viking '75
    b. same subcontractors as Viking '75
    c. same management interfaces as Viking '75
    d. only mandatory spacecraft changes assumed
4. lander and rover costs include 5% target fee
5. orbiter science assumed to be a repeat of the Viking '75 instruments (visual imaging system, Mars atmosphere water detector, and infrared thermal mapper)
6. cost estimates in FY'73 dollars
7. launch vehicle costs not included.

The estimated costs of the four adaptive missions are shown in Table VII-1.

Orbiter costs include the following cost categories related to the development and flight of the orbiter spacecraft.

1. project management and support
2. science support
3. mission analysis and engineering
4. orbiter engineering support
5. hardware subsystems
6. assembly, test and operations
7. ETR operations
8. mission operations

The lander costs shown in the table include the following categories of effort:

1. planning and control
2. mission design and flight operations
3. systems engineering
4. parts materials and processes
5. hardware subsystems
6. assembly test and launch operations
7. mission operations

The factor for lander modifications covers changes to the lander to integrate and land the new payloads.

The NASA support costs cover a number of government furnished equipment items and services.

The costs of adding adaptability to the mission are shown at the bottom of the table. These costs can be added directly to the totals for the non-adaptive missions. The adaptive control system costs cover the data acquisition, processing and

Table VII-1 Cost Estimate - Adaptive Mars Missions (1979)

(FY 73 Dollars in Millions)	Advanced Lander	Adv. Lander Standard Small Rover	Adv. Lander Deluxe Small Rover	Adv. Lander Medium Rover
Orbiter	78	78	78	78
Orbiter Modifications	--	--	--	3
Orbiter Science	10	10	10	10
Lander	113	113	113	113
Lander Modifications	5	5	5	8
Advanced Lander Science	80	80	80	80
Standard Small Rover		6		
Deluxe Small Rover			9	
Medium Rover				98
NASA Support	63	64	65	86
Cost - Non-adaptive Mission	349	356	360	476
Adaptive Control System	8	8	9	9
Adaptive Science Mods	12	12	12	15
Adaptive Operations Software	4	4	5	5
Cost - Adaptive Mission	373	380	386	505

interfacing equipment needed to convert the lander guidance control and sequencing computer into an adaptive controller. The adaptive science modes are changes that would have to be made to the fixed-sequence science instruments to permit them to function with the artificial intelligence systems to form an adaptive payload. The costs for adaptive operations software cover the development of the techniques and tools for programing, modifying and operating the adaptive mission.

As can be seen from these cost estimates the addition of adaptability as described in this study increases the cost of a Mars mission by about 7%.

The science payload assumed for the basic advanced lander is listed in Table VII-2 along with the estimated costs to develop and qualify these instruments. This same payload would be on the lander for each of the four mission configurations.

Table VII-2 Cost Estimate - Advanced Lander Science

(FY 73 Dollars in Millions)

Improved Facsimile Cameras with Magnifier	1
Advanced Biology	25
Wet Chemistry	20
Integrated Geology	15
Soil Water	3
Improved Seismometer	3
Improved Meteorology	2
1-Meter Drill	3
Improved Surface Sampler	2
Science Integration and Support	2
Target Fee (5%)	4
Total	80

B. ADAPTIVE MARS MISSION SCHEDULES

An important conclusion reached in this study is that adaptive missions can incorporate varying degrees of artificial intelligence and levels of sophistication. In other words, adaptability can and probably will be added to planetary missions in steps as we gain more confidence in the approach.

In this study, Mars missions in the 1979 through 1988 time period were considered as candidates for adaptive missions. Depending on the amount of emphasis given to Mars exploration in our space program, progress in developing and flying artificial intelligence for Mars spacecraft may be rapid or more conservative. Figure VII-1 outlines a conservative program of Mars missions showing where the spacecraft concepts described in this study might fit. Other mission configurations are of course feasible for any of these Mars launch opportunities. For example, a mission being given serious consideration at the present time uses minimally modified landers comprised of spare Viking '75 hardware, outfitted with medium rovers capable of sorties out to a kilometer from the landers. The minimal advanced lander as used here may have some new science instruments compared with Viking '75 but would not carry the full complement of experiments listed under the advanced lander configuration in this study.

To illustrate the major program activities and milestones involved in developing an adaptive mission to Mars, the 1981 launch opportunity was chosen as an example. Figure VII-2 is a simplified schedule for an advanced lander with small rover mission incorporating adaptive systems and launched in November or December of 1981. The early activities (1974, 5 and 6) would be supporting research and technology (SRT) work aimed at bringing

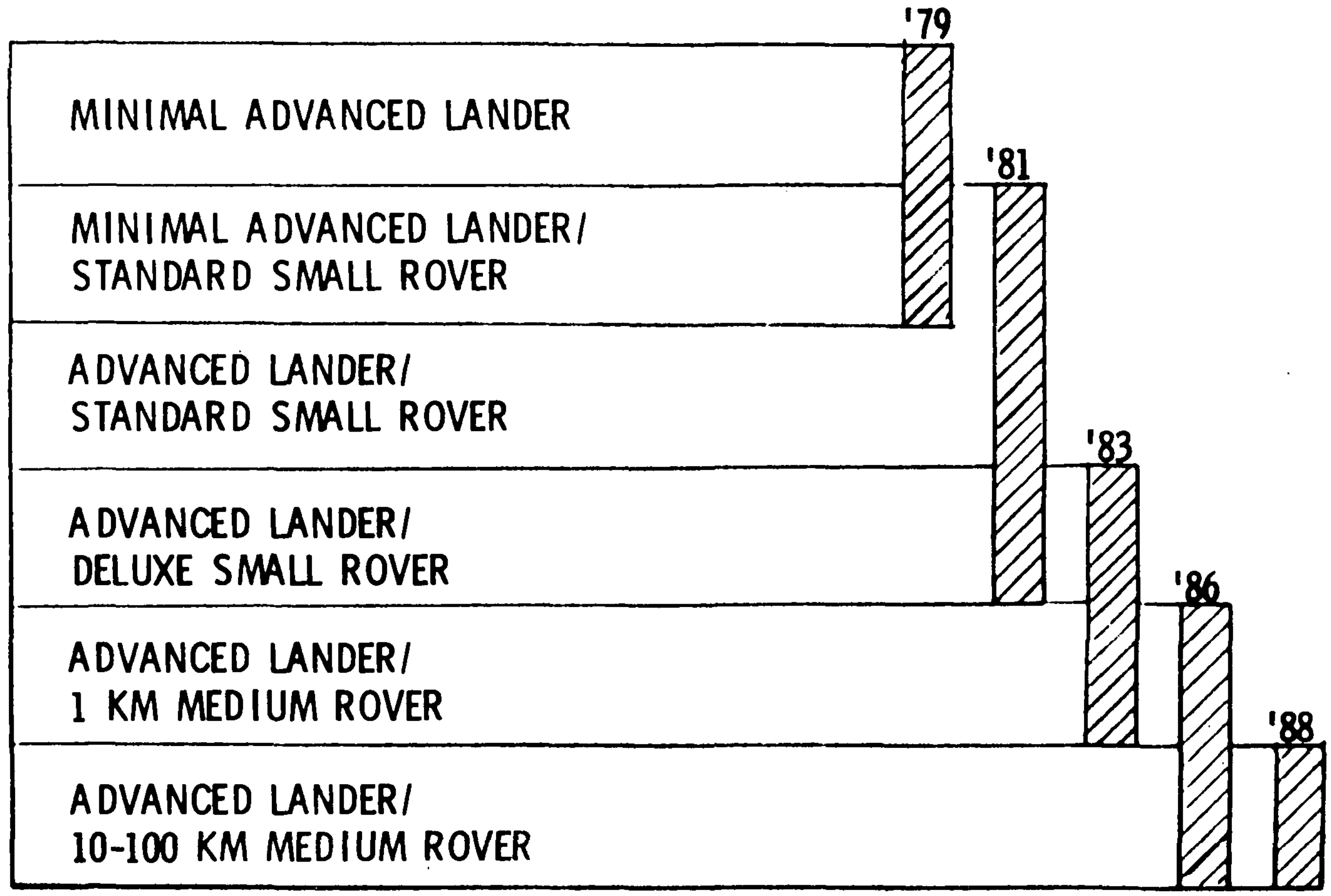

Figure VII-1 Adaptive Systems vs Mars Mission Opportunities

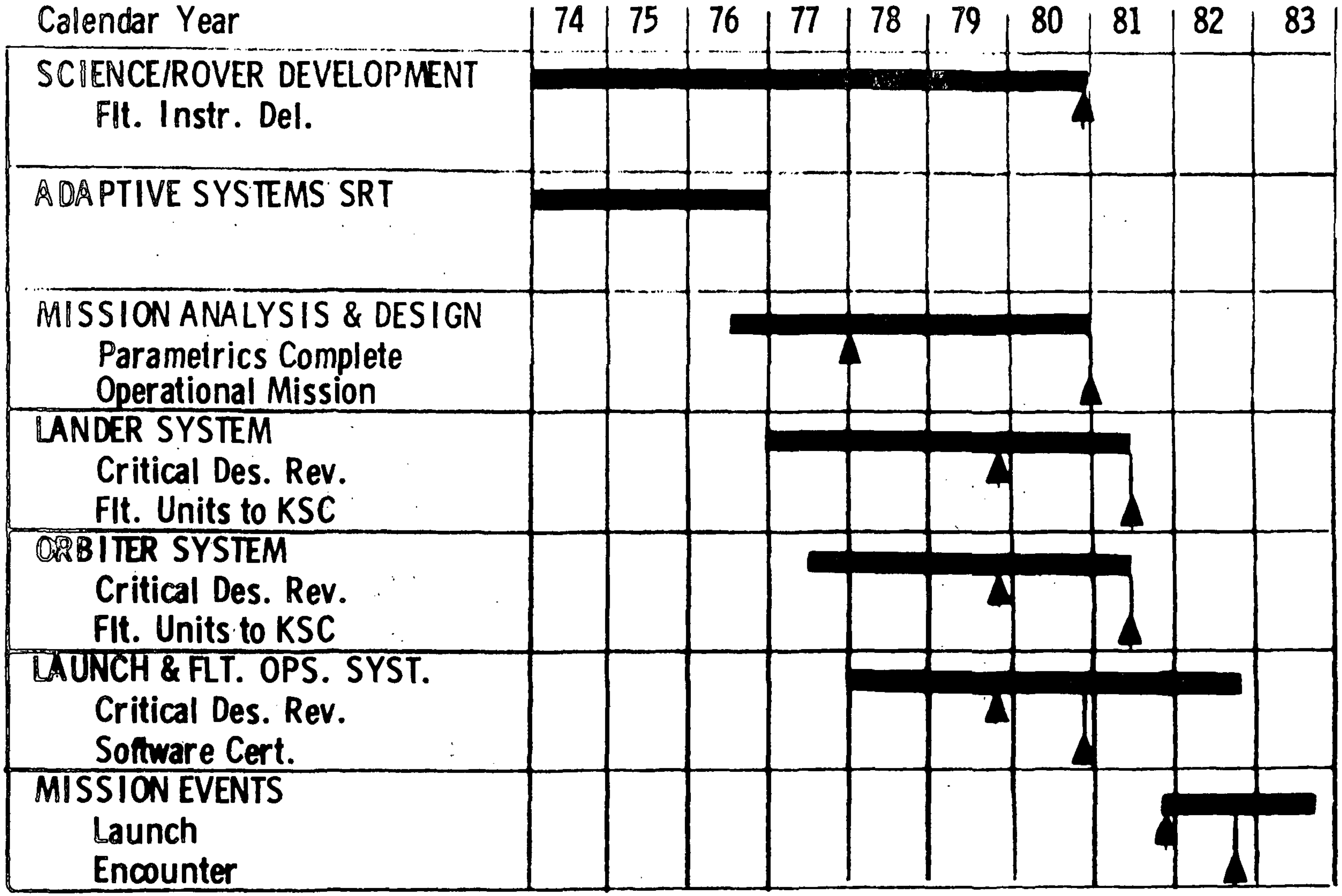

Figure VII-2 1981 Adaptive Mars Mission Schedule the rover, new science and adaptive systems technology development up to the prototype stage prior to full program go-ahead. This schedule assumes that the basic lander and orbiter configurations will be the Viking '75 designs, modified only as necessary to incorporate and deliver the new science, small rover and AI subsystems.

VIII. FUTURE TECHNOLOGY REQUIREMENTS

In the course of the study, items of technology were identified that need further development before they can be used in solar system exploration missions. Some are intimately connected with adaptability, and others will increase the value and versatility of both adaptive and non-adaptive missions. Some items will have important application in Earth-orbital and commercial systems.

The need for redundancy in critical spacecraft components has been recognized for a long time, but adaptive systems lend themselves particularly well to this way of increasing reliability since the management of redundancy is an adaptive function. Further work is needed in techniques for detecting malfunctions and switching in the back-up gear. The greater boost capability that will be available with Shuttle will permit cost savings by using redundancy rather than ultra-reliable components. Applications to control systems for mass transportation may be important.

A universal computer that can be used for most space vehicles is another cost saver. Its capacity could be adjusted to particular applications by adding memory modules and possibly by using multiple processors.

In the general area of adaptive control systems, a library of operating routines is needed. Algorithms that can extract interesting features from typical images have general utility not restricted to space exploration.

Engineering and scientific instrument developments for Mars landers and rovers include: a sample magnifier or microscope, miniaturized imaging systems for rovers including one that can get a detailed look at the ground, cable management for tethered rovers, and a wide variety of devices to gather and manipulate soil and rock samples.