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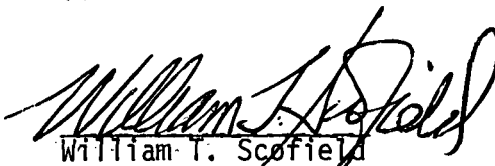
Contract NAS1-11711

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

Volume II
Survey of Solar System Missions

Approved


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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

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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.

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I. INTRODUCTION

In the long debate over the relative value of manned and unmanned space exploration missions, strong points stand out on each side.

Unmanned spacecraft can be significantly smaller and cheaper because they neither have to support man nor return him. Because of this they can also be committed to more risky and perhaps more interesting missions that would be unsafe or inhospitable to man.

Manned missions on the other hand offer the undisputable advantage of having human intelligence on board to react, to discriminate, to interpret, and to make useful decisions in response to what is found.

It is the objective of this study to identify ways in which human intelligence might be simulated on board an unmanned mission to achieve some of the decision-making capability or adaptability of the manned mission. It should be emphasized at the outset that in searching for adaptive features or artificial intelligence concepts, care was given not to sacrifice the relative cost and simplicity advantages of unmanned spacecraft missions. As a result of this approach, this study will favor and recommend simple, reliable techniques for making on board decisions and for modifying mission science operations in response to findings. The governing criterion for an adaptive system has been: the greatest increase in science value and flexibility for the least cost and complexity.

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 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 volume summarizes the results of the first part of the study in which twenty planetary missions were examined and ranked for their adaptive potential.

A. PLANETARY MISSIONS STUDY APPROACH

The unmanned planetary exploration missions treated in this study are listed in Table I-1. They include examples from all the classes of missions currently being considered in NASA long range planning activities. For purposes of this study it was assumed that these missions would be flown in the late 1970's to the late 1980's time period.

Table I-1

Mercury Orbiter	Encke Rendezvous
Venus Orbiter	Vesta Rendezvous
Venus Probe	Jupiter Orbiter
Venus Balloon	Jupiter Probe
Venus Lander	Saturn Orbiter
Mars Orbiter	Saturn Probe
Mars Lander	Uranus Orbiter
Mars Lander/Rover	Uranus Probe
Halley Flyby	Neptune Orbiter
Encke Flyby	Neptune Probe

In order to determine the role of adaptive systems and to establish a basis for comparison among missions, it was necessary to perform an identical series of study tasks on each of them. Figure I-1 outlines the steps followed to define each mission, examine its science and operational sequence, identify the possible role of adaptive systems, size the artificial intelligence (computer logic, etc.) required to implement these adaptive systems, and evaluate the resulting adaptive mission.

The key step in this study flow is the block titled Adaptive Modes. Here the study participants worked through the anticipated sequence of events in the mission, made assumptions about the scientific measurements, transient events and combinations of observations that might occur, and then defined the intelligent decisions or mission modifications that could be made to improve the scientific return. The situation was approached as though an observant and obedient technician were on board the spacecraft and the question was asked "what things should he watch for and what reactions should he make?" Artificial intelligence logic was then designed to detect such conditions and direct the appropriate reactions.

One of the most interesting and gratifying results of the study was that the on board decisions identified as potential enhancers of mission value, did not require extensive on board computer and control logic to carry out.

After defining each of the twenty planetary spacecraft and missions, identifying possible adaptive modes and sizing the required artificial intelligence to carry them out, it remained to rank all the missions to determine which offered the greatest potential for adaptability. This would help determine which missions warranted further study.

This ranking process was approached in two ways. First a number of objective, numerically measurable, parameters were identified that seemed to have a bearing on how much a given mission would benefit from on-board decisions and flexible mission sequences. These parameters included:

- 1) round trip communication time (how long it takes to make a decision under Earth control)

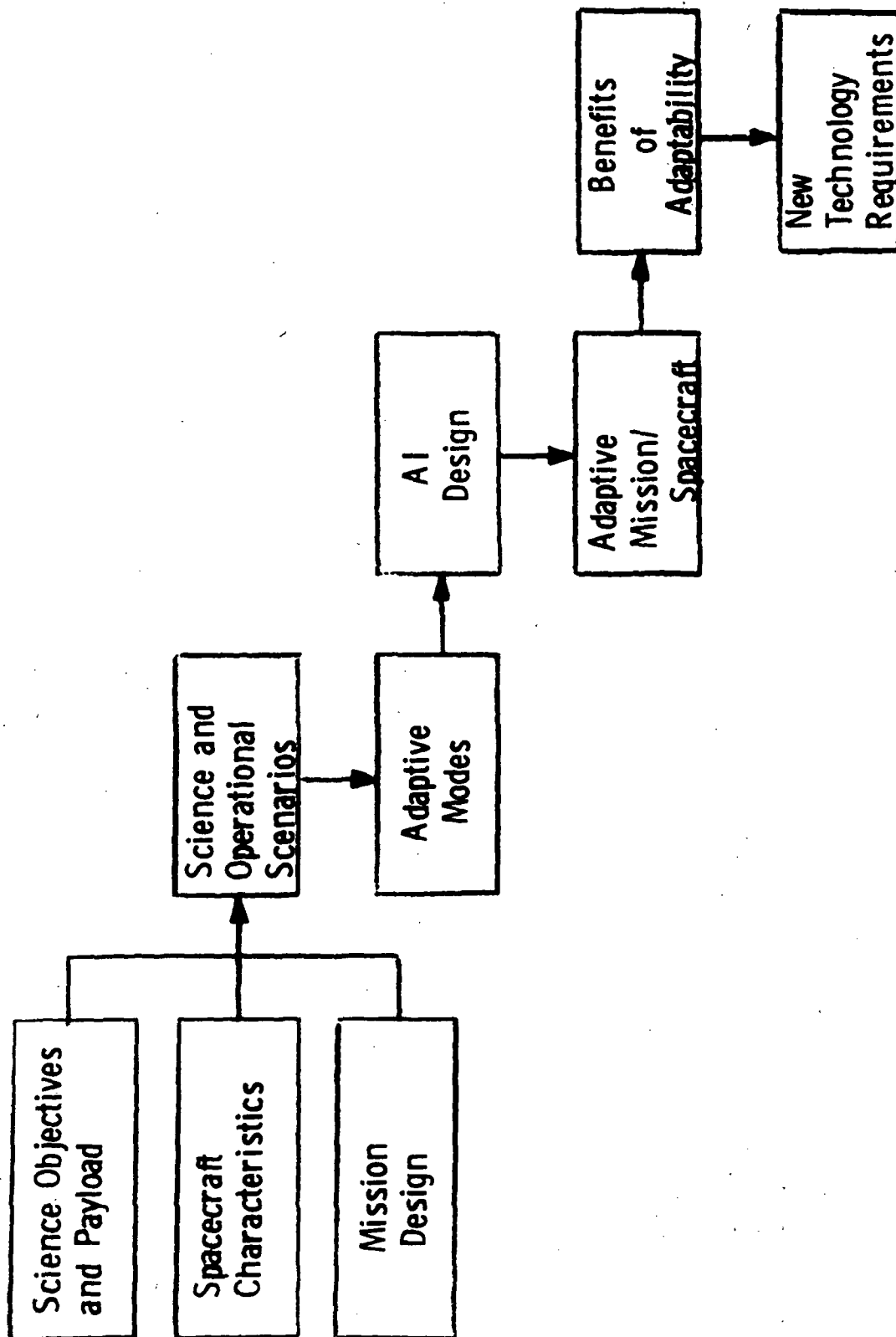


Figure I-1 Adaptive Missions Study Approach

- 2) science mission duration (how much time is available to make decisions)
- 3) mission duration divided by round trip communications time (how many Earth controlled decisions could be made during the mission)
- 4) available data rate (how fast science data can be returned to Earth)
- 5) total available data volume (how much data can be returned during the mission)
- 6) science weight available
- 7) spacecraft power available

Each of the 20 missions was measured against these parameters and a ranking made. The mission duration divided by round trip communications time, or normalized mission duration, was a good measure of the potential value of adaptability since missions could be ranked by this parameter for communication and control difficulty from Earth. Figure I-2 shows the results of this comparison. It can be seen that the short lived outer planets probes missions have the shortest normalized mission durations. This would indicate that these missions would provide very little opportunity to react to transients, explore unexpected measurements with other sensors or modify science priorities or sequences unless these actions are controlled on-board the spacecraft.

The resulting ranking of missions based on comparison of all of the numerically measurable parameters was as follows:

- 1) Outer Planet Probes
- 2) Venus Probes and Landers
- 3) Halley and Encke Flybys
- 4) Neptune, Uranus and Saturn Orbiters
- 5) Venus Valloons

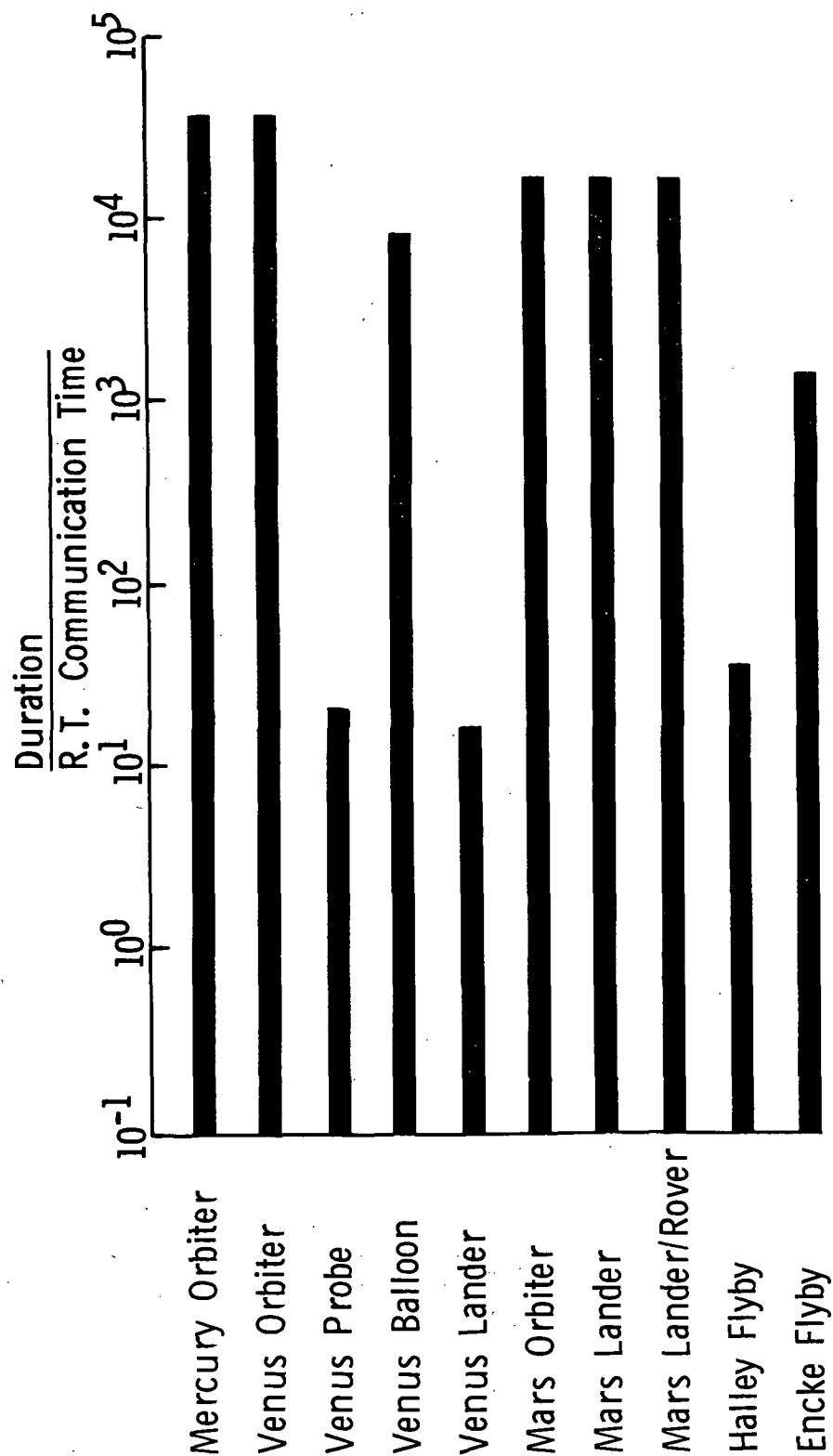


Figure I-2 Normalized Mission Durations

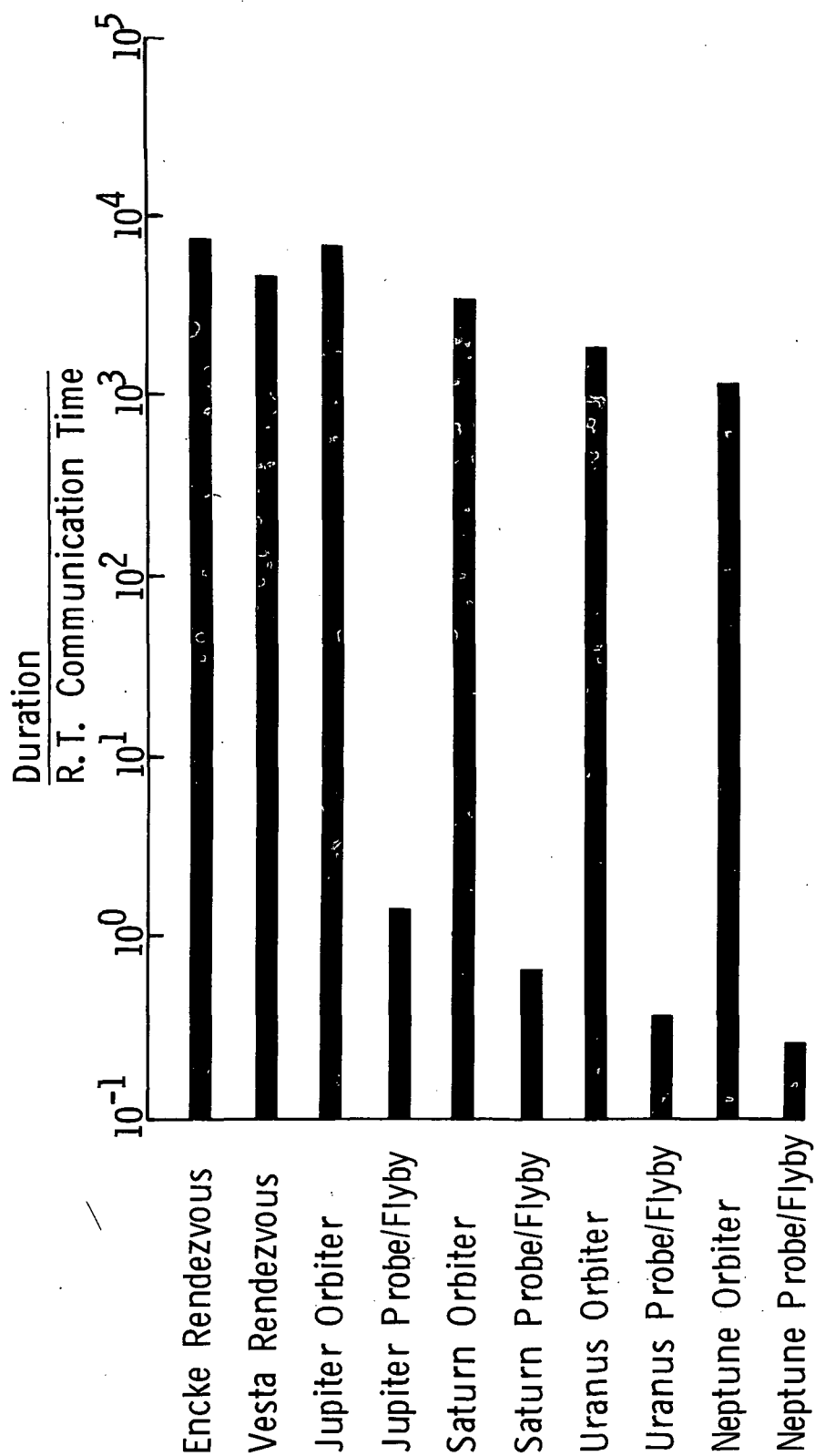


Figure I-2 Normalized Mission Durations (concluded)

- 6) Mars Lander/Rovers
- 7) Mars Landers
- 8) Jupiter Orbiter, Vesta and Encke Rendezvous
- 9) Mars, Mercury and Venus Orbiters

The second approach to ranking the planetary missions for the potential value of making them adaptive was, of necessity, more subjective. It involved examining factors such as the following:

- 1) number and apparent benefits of the adaptive modes identified for the mission in this study;
- 2) variety of science regimes to be explored (i.e., atmosphere, geosphere, biosphere, etc.);
- 3) expected transients and dynamics;
- 4) complexity of expected transients and dynamics and the degree of interaction among them.

The final ranking of planetary missions based on both evaluation approaches indicated that these mission classes would benefit most by the incorporation of artificial intelligence to make them adaptive:

- 1) Mars Lander/Rovers
- 2) Outer Planets Probes
- 3) Venus Probes/Landers
- 4) Comet Flybys
- 5) Outer Planet Orbiters

II. DESCRIPTION OF MISSIONS

A. SUMMARY OF MISSION PARAMETERS

Table II-1 indicates some of the pertinent performance and mission planning data for a variety of solar system missions in the 1980s. An attempt was made to select a "best" mission in the 80s for each planet, Halley's comet, Encke, and the asteroid Vesta using available data. In several cases, however, two missions are indicated because the simplest mission yields inadequate payload capability for the mission. An example of this is the Mercury mission, which has a feasible payload in orbit of 105 kg for the direct mission and 890 kg for the mission using a Venus "swing by." Additional missions to Uranus and Neptune are shown to illustrate the Solar Electric Propulsion (SEP) capabilities since the chemical mission payloads are quite small. The injected spacecraft weights indicated assume the use of the Shuttle/Centaur launch system as described in the NASA "Launch Vehicle Estimating Factors for Advance Mission Planning," 1972 Edition. The High Energy Burner II (2300) stage was utilized whenever the payload without this stage was below 1200 kg. In some cases (Venus and Mars) the use of the Shuttle/Centaur yields excessive payloads and adequate payloads could be obtained by a less powerful launch system such as Titan IIIE/Centaur.

The capture orbits selected for this table rely on previous studies where available and where they are not, a loose capture orbit is selected to reduce the propulsion requirements for the orbit insertion maneuver. Because of the relatively high orbit insertion ΔV requirements for many of the missions, a space storable propulsion system ($I_{sp} = 385$ sec) was utilized for all orbital missions. A 10% increase to the orbit insertion requirements was made to allow for navigation, midcourse, and finite burn loss requirements. The flyby weights are the injected

Table II-1 Mission Characteristics

Mission	Launch Year	Injec C3 (KM/SEC) ²	Inj S/C Wt ^① (KG)	Enc Vel (KM/SEC)	Capture Orb. Planet Radii/Period	Orbit Insertion ΔV (MPS)	Trip Time (Yrs)	R/T Com Time (MIN)	In-Orbit Wt ^② ^⑥ (KG)	Flyby Wt ^⑦ (KG)
Mercury Orbiter (Direct)	1986	89	1630	8.05	1.2 x 23/2.5 days	5155	0.38	8- 25	105	----
Mercury Orbiter* (Venus Gravity Assist)	1980	34	4850	6.80	1.2 x 9.7/.74 days	4170	1.83	8- 25	890	----
Venus Orbiter*	1983	7	8390	4.05	1.07 x 1.97/2.7 hours	2737	.43	5- 29	3060	----
Venus Lander*	1983	7	8390	4.05	1.07 x 1.97/2.7 hours	2737	.43	5- 29	1060 Orbiter 2000 Lander(s)	----
Mars Orbiter*	1988	13	7250	2.8	1.44 x 10.9/24.6 hours	1117	.58	7- 44	4900	----
Mars Lander*	1988	13	7250	2.8	1.44 x 10.9/24.6 hours	1117	.58	7- 44	800 Orbiter, 4100 Lander(s)	----
Jupiter Orbiter (Direct)*	1980	90	1990 ^④	6.0	4x56/20 days	1612	3.33	65-108	1080	----
Jupiter Probe*(Mars Grav. Asst)	1982	66	2580	6.1	-----	-----	3.56	65-108	-----	2300
Saturn Orbiter (Direct)*	1986	109	1400 ^④	6.1	2.5x125/89 days	1036	4.90	133-183	930	----
Saturn Probe*(Jup. Grav. Asst)	1979	109	1400 ^④	12.4	-----	-----	3.17	133-183	-----	1245
Uranus Orbiter*(Sat. Grav. Asst)	1980	137	930 ^④	13.2	1.5x75/26 days	4476	7.15	285-350	80	----
Uranus Probe*(Sat. Grav. Asst)	1980	137	930 ^④	13.2	-----	-----	7.15	285-350	-----	830
Uranus Orbiter ^③ (Saturn Gravity Assist)	1982	63 + 26 KWSEP	1270	11.3	1.5 x 75/26 days	3413	7.23	285-350	275	----
Uranus Probe ^③ (Saturn Gravity Assist)*	1982	63 + 26 KWSEP	1270	11.3	-----	-----	7.23	285-350	-----	1130
Uranus Orbiter ^⑧ *	1982	Escape + 100 KWNEP	-----	Spiral	2.0 x 38/9.7 days	-----	5.8	285-350	1000	----
Neptune Orbiter (Saturn Gravity Assist)	1986	120	1200 ^④	15.0	1.5 x 75/22 days	5166	8.5	480-520	75	----
Neptune Probe (Sat. Grav. Asst)	1986	120	1200 ^④	15.0	-----	-----	8.5	480-520	-----	1070
Neptune Orbiter ^③ (Saturn-Uranus Gravity Assist)	1982	63 + 26 KWSEP	1270	11.8	1.5 x 75/22 days	3398	11.6	480-520	315	----
Neptune Probe ^③ (Saturn-Uranus Gravity Assist)*	1982	63 + 26 KWSEP	1270	11.8	-----	-----	11.6	480-520	-----	1070
Neptune Orbiter ^⑧ *	1986	Escape + 100 KWNEP	-----	Spiral	14 x 14/4.9 days	-----	8.8	480-520	1000	----
Halley's Comet Flyby *	1984	120	1200 ^④	87.0	-----	-----	1.17	26	-----	1135
Encke's Comet Flyby *	1980	68	2540	21.0	-----	-----	0.22	23	-----	2400
Encke's Comet Rendezvous	1980	72	2360	.3	Stop Outside SOI	300+3600 Midcourse	3.6	32	465	----
Encke's Comet Rendezvous ^⑧ *	1982	Escape + 100 KWNEP	-----	-----	Stop Outside SOI	-----	1.4	32	1000	----
Vesta Rendezvous ^⑤ (Mars Gravity Assist)*	1986	12	7390	3.0	Stop Outside SOI	3000 ^⑥	1.69	25- 35	1035	----

① Shuttle/Centaur capability

② Weight delivered with space storable propulsion system - does not include propulsion system weight.

③ Solar electric propulsion used to obtain required trajectory - then is jettisoned.

④ Utilizes HE Burner II (1440).

⑤ 1600 mps burn at Mars swingby.

⑥ Assumes additional 10% ΔV for midcourse corrections, ΔV_{STAT}, etc.

⑦ 100 mps midcourse correction per each planet-to-planet portion -- monopropellant -- weight does not include propulsion system (.8 mass fraction).

⑧ Nuclear Electric Propulsion.

weights reduced by the weight of the propulsion system required for the midcourse corrections. The midcourse corrections are assumed to be 100 mps for each planet-to-planet trajectory, i.e., for a gravity assist from one planet the MCC is 200 mps and from two planetary gravity assists is 300 mps.

The Encke rendezvous mission utilizes a large midcourse maneuver of 3600 mps to match the orbital planes of the spacecraft and Encke. This maneuver yields a very small closure rate (VHE) of 300 mps. The Vesta rendezvous mission utilizes a powered Mars swingby where 1600 mps is applied to yield the proper trajectory to Vesta.

The flyby mission geometry is depicted in Appendix B along with the orbital geometry for the orbital mission.

B. SCIENTIFIC OBJECTIVES AND TECHNIQUES

Table II-2 lists the objectives and techniques that were assumed for the study of the applications of adaptability. The list was compiled from the reports and other literature shown in the bibliography following Table II-2.

Table II-2 Scientific Objectives and Techniques	
<u>Scientific Objective</u>	<u>Technique</u>
<u>Mercury Orbiter</u>	
Surface topography	Imagery
Terrain elevation	Radar or laser altimetry, imagery
Figure, spin axis	Imagery
Mass	Tracking transponder
Surface thermal anomalies	IR radiometric mapping
Magnetic field	Magnetometry
Radiation belts (if present)	Ionizing particle detection
Atmosphere: composition, mean molecular weight, and surface pressure	UV photometry, radio occultation
Surface composition heterogeneity	IR spectrometry
Radioactive elements	Gamma-ray spectrometry
Major elements	X-ray fluorescence (if atmosphere permits), gamma-ray spectrometry
<u>Venus Orbiter</u>	
Surface topography	Imaging radar
Total mass, mass distribution	Tracking transponder
(continued)	

Table II-2 Scientific Objectives and Techniques (continued)

<u>Scientific Objective</u>	<u>Technique</u>
<u>Venus Orbiter</u> (concluded)	
Magnetic field, interaction of the planet with solar magnetic field	Magnetometry
Surface thermal pattern	Microwave radiometry
Atmospheric structure	IR limb scanning, dual-frequency occultation
Cloud patterns, composition, motion	Imagery, IR spectrometer, UV photometric mapping
Ionospheric composition, temperature, and electron density	Ion and neutrals mass spectrometry, retarding potential analyzer, electron temperature probe, topside sounding
Surface roughness, slopes, electrical properties	Bistatic radar
Ionosphere interaction with solar wind	Plasma wave monitor, magnetometry, solar wind probe
<u>Venus Probe/Buoyant Station</u>	
Cloud morphology, haze detection	Imagery
Cloud particle size distribution	Laser beam particle shadowing
Wind velocity	Interferometric and doppler tracking transponder
Atmospheric transparency, scattering, particle size and density	Solar aureole and extinction detection
Meteorological parameters	Temperature, pressure, wind velocity vector, condensation, hygrometry
Atmospheric composition	Shock layer radiometry, neutral mass spectrometry, x-ray fluorescence spectrometry

(continued)

Table II-2 Scientific Objectives and Techniques (continued)

<u>Scientific Objective</u>	<u>Technique</u>
<u>Venus Probe/Buoyant Station</u>	
If Buoyant	
Wind patterns	Tracking transponder (to orbiter, if present)
Temporal changes in cloud composition, dynamics, thermodynamic state	Most of above techniques
Aerosol collection and analysis	Filters or electrostatic precipitation; laser-stimulated emission spectroscopy
<u>Venus Lander</u>	
Internal activity/structure	Passive seismometry
Internal structure	Active seismometry
Surface composition	
Major and minor elements	Neutron activation or x-ray fluorescence analysis
Mineralogy	X-ray diffraction
Radioactive elements	Gamma-ray spectrometry
Atmospheric composition	Mass spectrometry, hygrometry, condensimetry
Meteorological parameters	Pressure, temperature, wind velocity instrumentation
Atmospheric electricity	Sferics detection, sonic noise detection
Local topography	Active imagery
Eolian properties	Dust collector, wind velocity, particle size analyzer
Atmospheric transparency	Solar aureole and extinction detection
Surface physical properties	Subsurface temperature probe, penetrometer

(continued)

Table II-2 Scientific Objectives and Techniques (continued)

<u>Scientific Objective</u>	<u>Technique</u>
<u>Mars Orbiter</u>	
Surface morphology, granularity	High resolution, extended range (visible, near IR, and UV) imagery
Surface slopes, roughness, bulk electrical properties	Bistatic radar
Terrain elevation mapping	Radar altimetry or CO ₂ pressure mapping (IR)
Compositional heterogeneity	IR spectrometric (near through thermal) mapping
Radioactive elements	Gamma-ray spectrometry
Subsurface stratigraphy, permafrost	Microwave radiometry, radar sounding
<u>Mars Lander</u>	
Geologic setting	Multispectral imagery
Detection of life	Metabolism detection via gas exchange, carbon-14 and stable-isotope tracers. Growth via light scattering.
Organic compounds	Gas chromatograph/mass spectrometry, amino acid/optical activity chromatography
Atmospheric composition	Atmospheric gas chromatograph/mass spectrometry
Meteorological parameters	Temperature, pressure, wind velocity vector, balloons, rocketsondes
Composition of surface material	
Major and minor elements	X-ray fluorescence, alpha backscatter
Trace elements	Neutron activation analysis
Mineralogy	X-ray diffraction
Fabric and texture	Petrographic magnifier
Water (bound and unbound), adsorbed and bound gases	Differential scanning calorimetry, evolved gas analysis
(continued)	

Table II-2 Scientific Objectives and Techniques (continued)

<u>Scientific Objective</u>	<u>Technique</u>
<u>Mars Lander</u> (concluded)	
Crystallization age	K/Ar dating
Regolith moisture, permafrost	Neutron backscatter, microwave radiometry
Subsurface structure	Active seismometry; network seismometry of natural events; microwave radiometry; radar sounding
Heat flow	Drill core temperature probes
Seismic activity	Seismometry
Physical and magnetic properties	Penetrometry, imagery-related physical properties, magnet experiment
<u>Jupiter Probe/Flyby</u> (Also Saturn, Uranus, Neptune)	
Mass	Flyby spacecraft tracking
Radius, figure, rotation	Imagery
Atmospheric composition and isotopic ratios	Neutral mass spectrometry, UV photometry
Atmospheric structure	Probe descent profile, radio signal attenuation, temperature, pressure
Ionospheric composition and structure	Ion mass spectrometry, Langmuir probe, radio frequency noise detection, plasma wave detection
Cloud compositions and locations	Nephelometry, neutral mass spectrometry, UV photometry
Magnetic field	Magnetometry
Radiation belts	Ionizing particle identification, flux density, and energy spectrometry, plasma wave detection
(continued)	

Table II-2 Scientific Objectives and Techniques (continued)

<u>Scientific Objective</u>	<u>Technique</u>
<u>Jupiter Orbiter</u> (Also Saturn, Uranus, Neptune)	
Total mass, internal mass distribution	Spacecraft tracking
Radius, figure, rotation	Imagery, occultation
Atmospheric structure	Dual frequency occultation
Atmospheric composition	IR radiometry and spectrometry, UV spectrometry (airglow and occultation), photopolarimetry
Cloud patterns and motions	Imagery, IR and UV mapping
Heat flow	IR radiometry
Magnetic fields, static and dynamic components	Vector helium and fluxgate magnetometry
Radiation belts	Ionizing particle identification, flux density and energy spectrometry
Ionospheric composition, temperature, and electron density	Ion and neutral mass spectrometry, retarding potential analyzer, electron temperature probe, topside sounding
Physical and chemical properties of exospheric particles	Optical particle detection (sisyphus), zodiacal light mapping, impact detection
Ionospheric interaction with solar wind	Solar wind probe, plasma wave monitor, magnetometry, radio emissions
X-ray emissions	X-ray mapping spectrometry
Satellite studies	(See Asteroid Flyby, Mercury Orbiter)
Satellite-planet interactions	Magnetometry, charged particle spectrometry, solar wind probe, topside sounder, imagery, dual frequency occultation

(continued)

Table II-2 Scientific Objectives and Techniques (continued)

<u>Scientific Objective</u>	<u>Technique</u>
<u>Asteroid Rendezvous (Vesta)</u>	
Orbital elements	Star field imagery + spacecraft transponder
Rotational motions	Sequential imagery
Mass	Spacecraft tracking
Volume	Imagery analysis
Bulk density	From mass and volume
Impact and accretive history	Surface morphology (imagery)
Surface composition	Reflection spectrum (visible, near and mid-IR spectrometry) Solar-excited x-ray fluorescence Thermal inertia (IR radiometry) Radioactive elements (gamma-ray spectrometry)
Homogeneity of surface composition	Mapping spectrometry (all preceding techniques possible)
Internal mass homogeneity	Rotational motions (imagery) Gravity-gradiometry
If Touch Down	
Major and minor elements	Alpha backscatter, x-ray fluorescence
Mineralogy	X-ray diffraction
Organic compounds	Pyrolyzer/mass spectrometry
Crystallization age	K/Ar dating
<u>Halley and Encke Fast Flybys</u>	
Size and structure of the nucleus and coma	Imagery, radio occultation, bistatic radar
Albedo and surface texture	Photopolarimetry
Density and composition maps of gas molecules	Neutral mass spectrometry

(continued)

Table II-2 Scientific Objectives and Techniques (concluded)

<u>Scientific Objective</u>	<u>Technique</u>
<u>Halley and Encke Fast Flybys (concluded)</u>	
Density and composition maps of ions and radicals	Spectrophotometry, ion mass spectrometer
Energy spectrum of ions and electrons	Electrostatic analysis
Electron density	Langmuir probe, plasma wave detection
<u>Encke Rendezvous</u>	
Size and structure of the nucleus and coma	Imagery, radio occultation, solar occultation, bistatic radar
Mass (techniques may be marginal)	Tracking transponder, gravity gradiometry
Shapes and dynamic motions of nucleus (rotations/librations)	Repetitive imagery
Albedo and surface texture	Photopolarimetry
Spatial distribution, size distribution, velocity of icy grains and solid particles	Optical particle detection (Sisyphus) photopolarimetry, impact detection
Density and composition maps of gas molecules	Neutral mass spectrometry
Density and composition maps of ions and radicals	Spectrophotometry; ion mass spectrometry
Energy spectrum of ions and electrons	Electrostatic analysis
Electron density	Langmuir probe, plasma wave detection
Size and shape of hydrogen cloud	Lyman alpha photometry
Magnetic fields	Fast tri-axial magnetometry

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C. SUPPORT SYSTEMS

This chapter describes the methods that were used and the results of a study of support subsystem sizes, weights and capabilities. Section C.-1 treats all subsystems and arrives at the weight available for the scientific payload. Section C.-2 is a more detailed analysis of the communication subsystems.

1. Spacecraft Subsystem Sizing

An empirical analytical technique for estimating the weight of unmanned planetary spacecraft which was developed under a separate company-sponsored study has been modified to support the planetary missions portion of this study. Both analytical and historical data have been used to relate spacecraft subsystems weight and electrical power requirements to mission and system parameters. The technique as developed is limited to: 1) flyby and orbiting spacecraft, 2) target planets from Venus to Neptune, and 3) state-of-the-art subsystem concepts. Subsystem weights for the Mars lander, rover, and outer planets probes were evaluated from data generated from the Viking '75 spacecraft program and MMC's Outer Planets Studies. In general the historical data used were obtained from the Mariner spacecraft series, Lunar Orbiter, Pioneer spacecraft series, and the Viking program. The flow diagram used in applying the technique is shown in Figure II-1.

For each subsystem, the mission and system design parameters that influence weight and power were identified. In several cases, the key design parameter was system weight (e.g., dry spacecraft weight) or system characteristic (e.g., total internally dissipated power). Obviously such parameters are not known

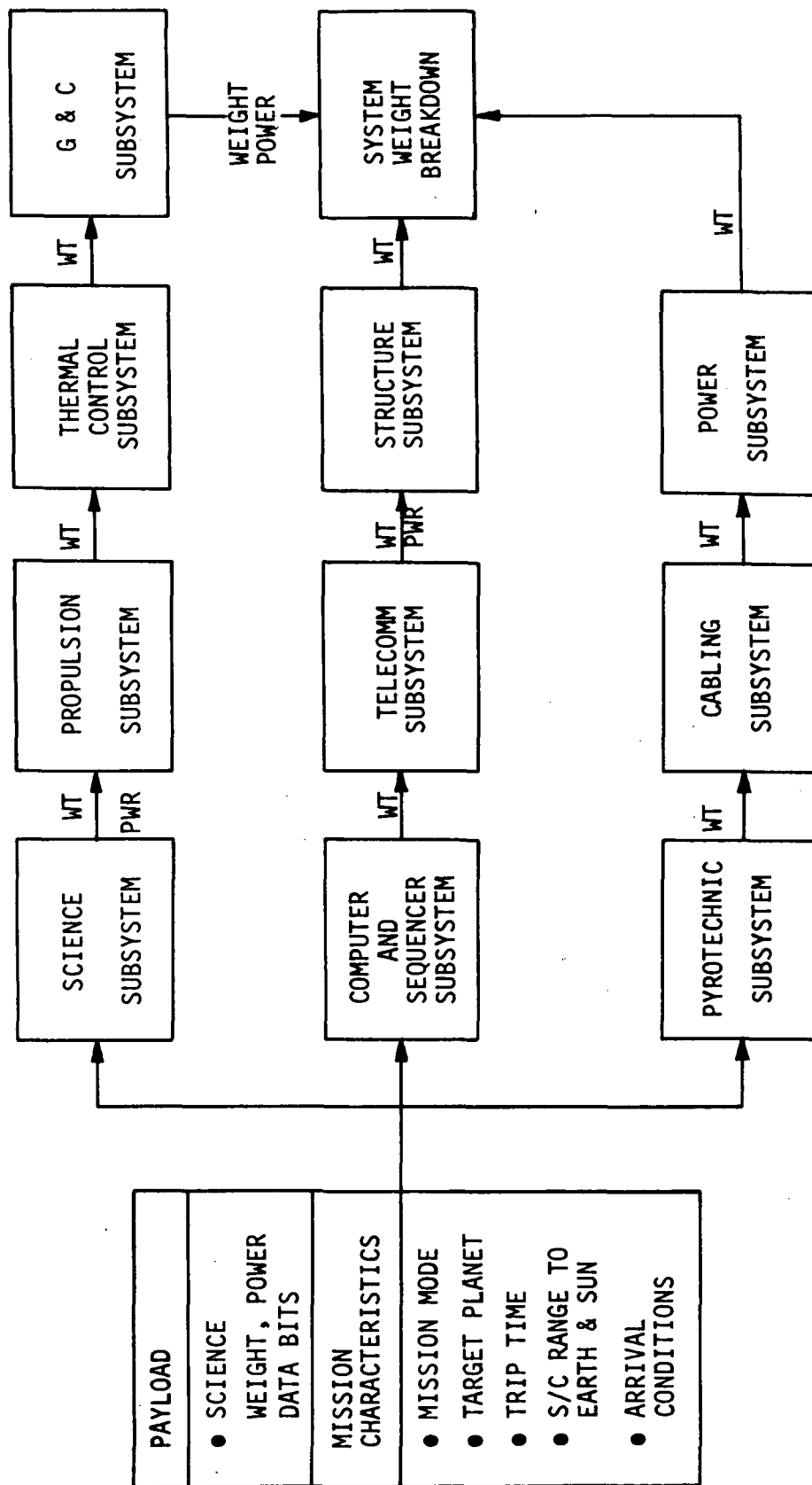


Figure II-1 Flow Diagram for Planetary Missions Spacecraft Sizing

a priori. Therefore, the technique is iterative. An initial estimate of unknown parameters (e.g., dry spacecraft weight) is made. Two or three iteration cycles are then required to make the results converge to the desired accuracy.

Three of the subsystems that make up the total system weight were found to be represented quite adequately as a percentage of the spacecraft dry weight. These subsystems were: 1) pyrotechnic, 2) cabling, and 3) the contingency allotment.

The structure subsystem weight was found to be a function of the weight that this subsystem supports during launch. It includes the complete spacecraft (orbiter or flyby, lander and/or probes as applicable, and propellants). The structure weight thus determined represents both primary and secondary structure and is shown in Figure II-2.

The propulsion subsystem includes propellant tankage, engine(s), supporting structure and plumbing. For sizing, the Viking Orbiter system was selected as the basic system from which the various spacecraft propulsion systems for each of the missions were developed. The final actual in-orbit weight or flyby weight is expressed by the following equation:

$$W_{\text{ORBITAL}} = (W_{\text{USEFUL}} + XK_1) / (1.0 + XK_2 - XK_2 * e^{\Delta V / g \text{Isp}})$$

where: XK_1 is the constant in the propellant inert equation

XK_2 is the propellant-dependent portion of the propellant inert equation

W_{USEFUL} is the desired useful weight in orbit

ΔV is the total of the velocity changes required for the mission

g is the Earth's gravity

Isp is the specific impulse of the engine (sec)

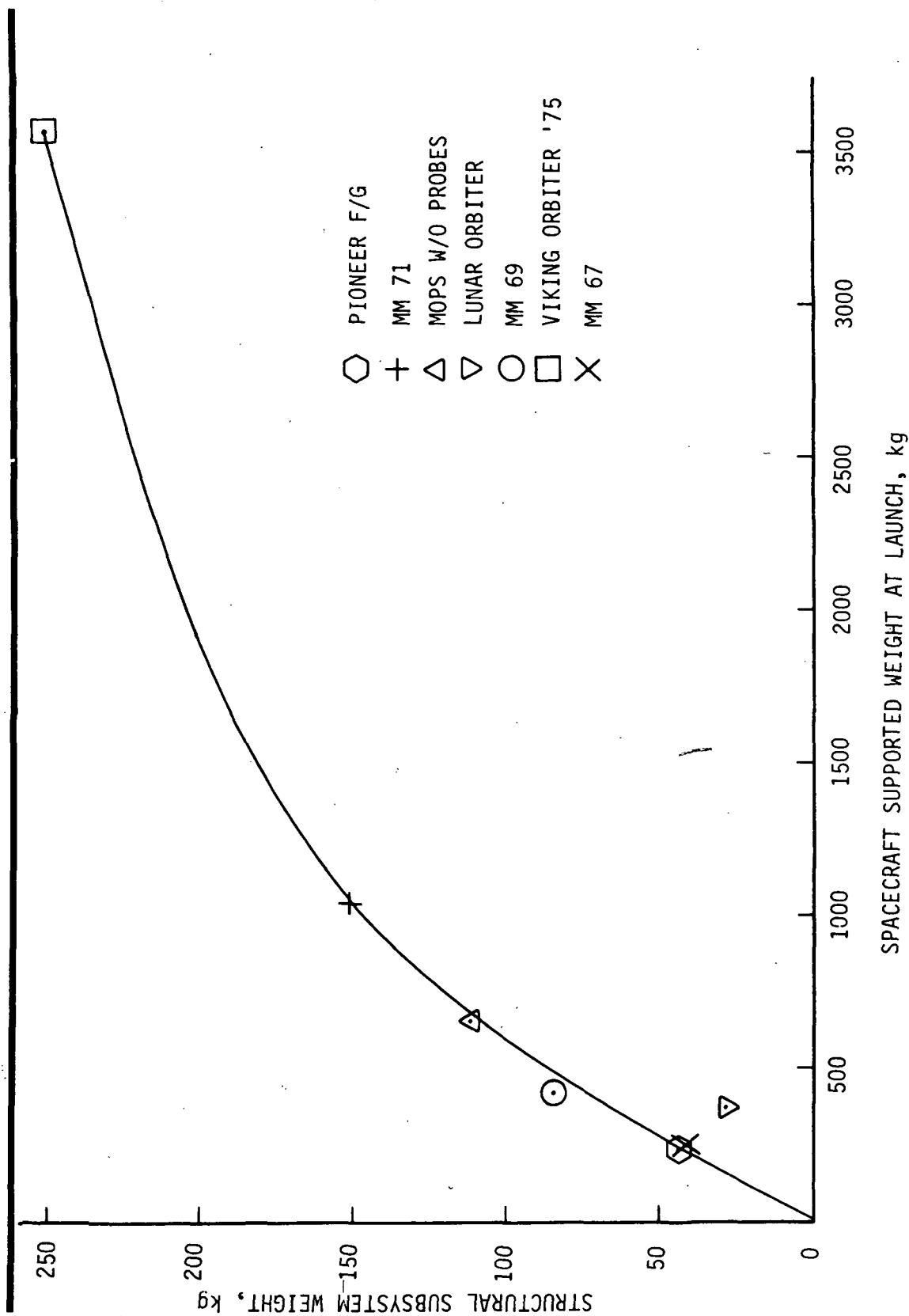


Figure II-2 Typical Approach to Spacecraft Subsystem Sizing - Structural Subsystem

The initial spacecraft weight (with its propellant) is

$$W_I = W_{\text{ORBITAL}} * e^{\Delta V / gIsp}$$

The propulsion system inert weight is

$$W_{\text{inert}} = 54 \text{ kg } (XK_1) + .129 \text{ (propellant weight) } (XK_2)$$

The propellant requirement then is simply the difference between the initial spacecraft weight and the actual weight in orbit.

The guidance and control (G&C) subsystem is made up of the G&C electronics, celestial and inertial sensors, attitude control assembly (thrusters, tanks, valves, and plumbing) and engine thrust vector control equipment. Figure II-3 shows the G&C subsystem weight for various mission durations for a typical 3-axis stabilized vehicle with a cold gas system.

Weight data for the computer and sequencing subsystem are shown in Figure II-4. This subsystem consists of the computing and sequencing electronics, the propulsion subsystem electronics, and the command electronics.

The temperature control subsystem concept considered here is semipassive. The major assemblies for this subsystem are louvers, surface coating, insulation, and thermal couplers. The weight of the thermal control subsystem as a function of spacecraft dry weight is shown in Figure II-5.

The telecommunications subsystem assumes advanced Mariner-class communications hardware technology at X-band as the primary basis. The system assumes a three-axis stable spacecraft capable of providing attitude pointing stability on the order of one-half of typical half-power beam width (HPBW) of the antennas to minimize pointing losses. Maximum radiated power was constrained to 20 watts, and maximum antenna diameter to approximately 3.7 meters

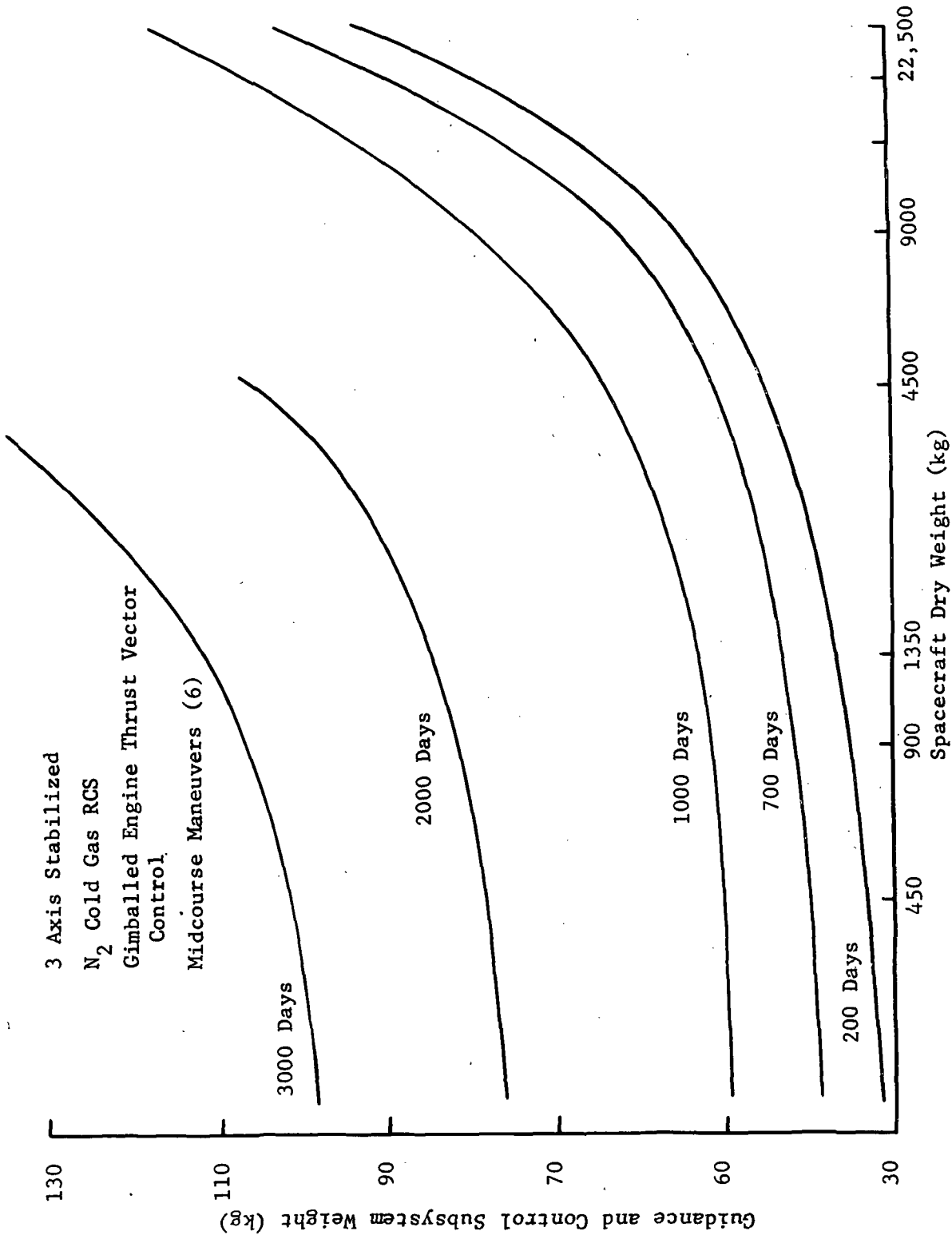


Figure II-3 Guidance and Control Subsystem Weight

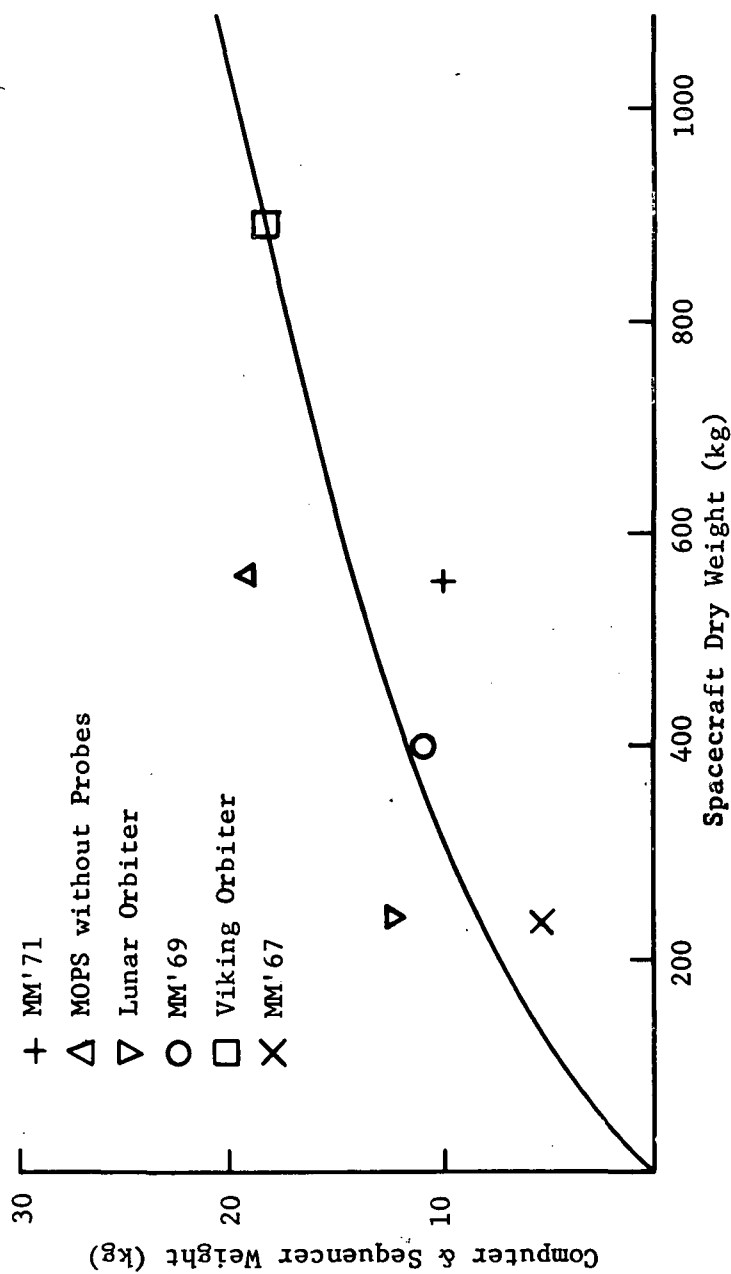


Figure II-4 Computer and Sequencer Weight

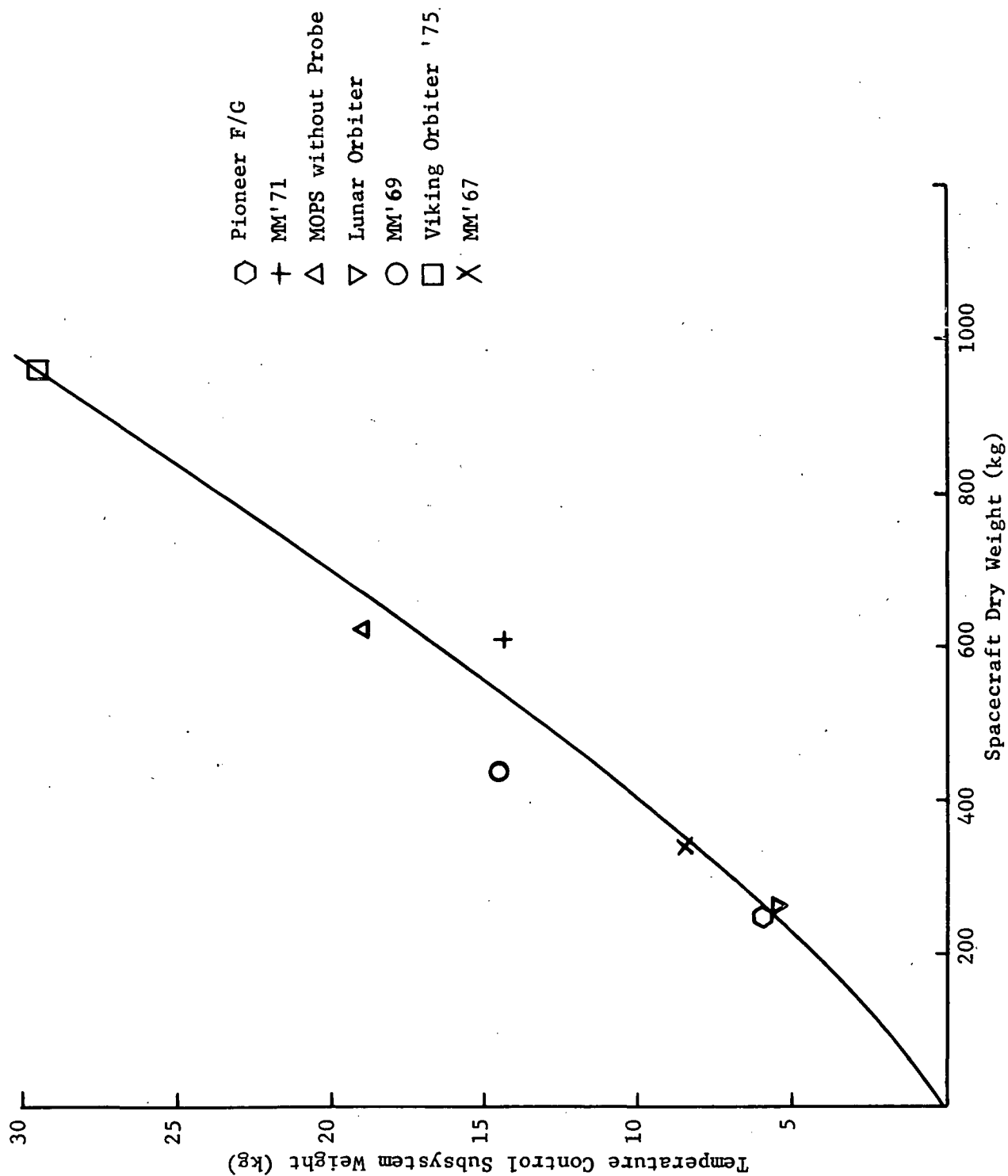


Figure II-5 Temperature Control Weight

(12 feet). Signal to noise as required for convolutional coding is assumed for data with one-way tracking techniques. The Mars and Venus landers use Viking-class technology operating at X-band. The probes use L-band and are extrapolated from MMC's outer planet probe studies*. The telecommunications subsystem weight for various planetary missions and spacecraft weight realms are summarized in Table II-3. A more detailed discussion of the telecommunications subsystem can be found in the following Section C.-2.

The powers available on board the flyby and orbiting spacecraft that were studied during the planetary missions study phase are shown in Figure II-6. Solar panel arrays were assumed for the inner planet, comet, and asteroid missions. Outer planet missions were assumed to utilize either four multi-hundred watt RTG's, supplying 520 watts of power, or nuclear electric propulsion (NEP) delivering 100 kilowatts.

Using the spacecraft sizing techniques, spacecraft weights were developed for each of the 20 planetary missions that were studied. These spacecraft weights are presented at the subsystem level in Table II-4.

The weight available for science implementation for each of the planetary missions is shown in Figure II-7. The science weights shown are consistent with the power and data capability available on board the orbiting or flyby vehicles. The weight available for science on board the planetary probes, balloons, and landers was determined by scaling up specific probes, balloons, and landers that were previously studied at MMC under contract to JPL, NASA/Goddard and NASA/LRC.

* *Outer Planet Entry Probe System Study Final Report.* JPL Contract 953311, August 1972.

Table II-3 Representative Communication Subsystems

Table II-3 Representative Communication Subsystems						
Spacecraft Weight Realms (kg)	RF Power	Antenna		Prime Power Inc. Recorder	Weight (kg)	
		Diameter	HPBW (deg)		Orb	Fby
<u>Orbiter & Flyby Missions</u>						
500	20 W (X-Band)	3.7m	.7	200	30	105
500	5 W (X-Band)	3.7m	.7	140	60	105
<u>Mars Lander</u>						
4000	20 W (X-Band)	.8m	3.3	200	105	
<u>Venus Lander</u>						
2500	5 W (X-Band)	.5m	5.2	140	60	
<u>Outer Planet Probes</u>						
125	40 W (L-Band)	Wide Beam (Spiral Slots)		100		8

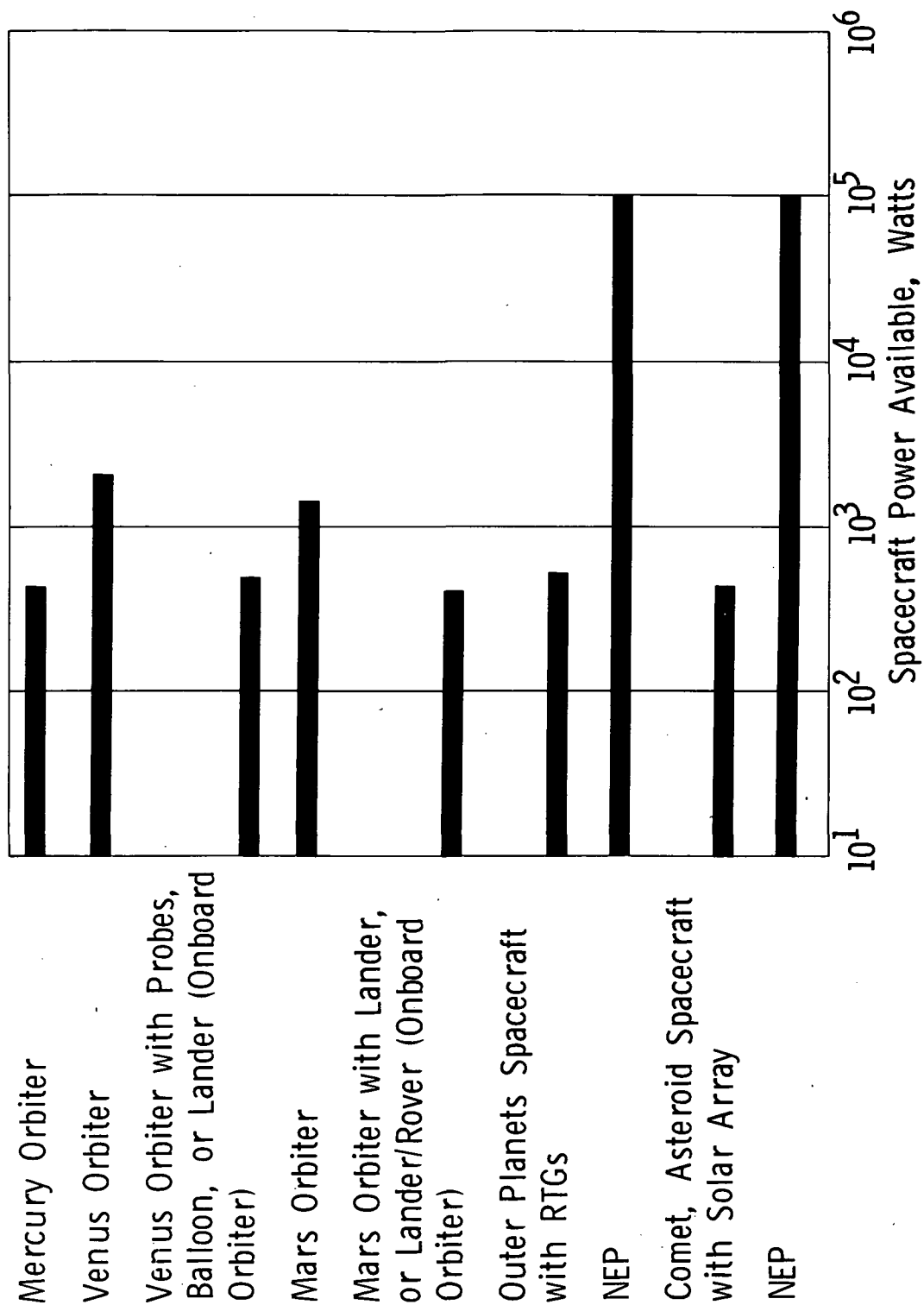


Figure II-6 Available Power

Table II-4 Subsystem Sizing (kg)

SUBSYSTEM	MERCURY ORBITER	VENUS ORBITER	SPACECRAFT WEIGHT (kg)		
			VENUS ORBITER/PROBES	VENUS ORBITER/BALLOON	VENUS ORBITER/LANDER
SCIENCE	127.0	1035.5	148.0/200.0	148.0/244.0	148.0/180.0
PROPULSION					
INERT	540.0	730.0	730.0	730.0	730.0
PROPELLANT	3420.0	4600.0	4600.0	4600.0	4600.0
STRUCTURE	338.0	850.0	390.0	390.0	390.0
GUIDANCE & CONTROL	43.0	75.0	65.0	65.0	65.0
COMPUTER & SEQUENCER	31.5	65.0	40.0	40.0	40.0
TELECOMMUNICATIONS	87.5	187.5	100.0	100.0	100.0
THERMAL CONTROL	28.0	75.0	36.0	36.0	36.0
PYROTECHNICS	21.0	45.0	27.0	27.0	27.0
CABLING	85.0	180.0	107.0	107.0	107.0
POWER	108.0	490.0	120.0	120.0	120.0
CONTINGENCIES	21.0	57.0	27.0	27.0	27.0
TOTAL DRY WEIGHT	1430.0	3790.0	1790.0	1790.0	1790.0
INJECTED WEIGHT	4850.0	8390.0	8390.0 ⁽¹⁾	8390.0 ⁽²⁾	8390.0 ⁽³⁾

Table II-4 Subsystem Sizing (continued)

SUBSYSTEM	MARS ORBITER	MARS ORBITER/ LANDER	MARS ORBITER/ LANDER/ROVER	HALLEY'S FLYBY	ENCKE FLYBY	ENCKE RENDZ.	VESTA RENDZ.
SCIENCE	2771.0	167/400	167/400	458.0	1287.0	361.0	111.0
PROPULSION							
INERT	350.0	350.0	350.0	11.0	23.0	-	850.0
PROPELLANT	2000.0	2000.0	2000.0	54.0	117.0	-	5505.0
STRUCTURE	950.0	231.0	231.0	252.0	560.0	300.0 ⁽⁵⁾	415.0
GUIDANCE & CONTROL	85.0	45.0	45.0	80.0	75.0	90.0	90.0
COMPUTER & SEQUENCER	65.0	30.0	30.0	25.0	53.0	22.0	41.0
TELECOMMUNICATIONS	187.5	100.0	100.0	87.0	87.0	87.0	87.0
THERMAL CONTROL	80.0	26.0	26.0	23.0	48.0	20.0	37.0
PYROTECHNICS	50.0	5.0	5.0	17.0	36.0	15.0	28.0
CABLING	120.0	51.0	51.0	68.0	110.0	60.0	90.0
POWER	490.0	133.0	133.0	108.0	108.0	30.0 ⁽⁶⁾	108.0
CONTINGENCIES	79.0	12.0	12.0	17.0	36.0	15.0	28.0
TOTAL DRY WEIGHT	5250.0	1150.0	1150.0	1146.0	2423.0	1000.0 ⁽⁷⁾	1885.0
INJECTED WEIGHT	7250.0	7250.0 ⁽⁴⁾	7250.0 ⁽⁴⁾	1200.0	2540.0	-	7390.0

Table II-4 Subsystem Sizing (continued)

SUBSYSTEM	JUPITER ORBITER	JUPITER FLYBY/PROBE	SATURN ORBITER	SATURN FLYBY/PROBE	URANUS ORBITER
SCIENCE	248.0	371.0/76.0	119.0	165.0/29.0	361.0
PROPULSION					
INERT	160.0	47.0	108.0	24.0	-
PROPELLANT	750.0	233.0	362.0	131.0	-
STRUCTURE	274.0	340.0	228.0	220.0	300.0 ⁽⁵⁾
GUIDANCE & CONTROL	105.0	110.0	160.0	110.0	90.0
COMPUTER & SEQUENCER	28.0	30.0	23.0	20.0	22.0
TELECOMMUNICATIONS	87.5	100.0	87.0	87.0	87.0
THERMAL CONTROL	25.0	27.0	21.0	18.0	20.0
PYROTECHNICS	19.0	20.0	15.0	14.0	15.0
CABLING	75.0	81.0	62.0	55.0	60.0
POWER	200.0	200.0	200.0	200.0	30.0 ⁽⁶⁾
CONTINGENCIES	19.0	21.0	15.0	14.0	15.0
TOTAL DRY WEIGHT	1240.0	1347.0	1038.0	927.0	1000.0 ⁽⁷⁾
INJECTED WEIGHT	1990.0	2580.0 ⁽⁸⁾	1400.0	1400.0 ⁽⁹⁾	-

Table II-4 Subsystem Sizing (continued)

SUBSYSTEM	URANUS FLYBY/PROBE	NEPTUNE ORBITER	NEPTUNE FLYBY/PROBE
SCIENCE	97.0/29.0	361.0	51.0
PROPULSION			
INERT	24.0	-	34.0
PROPELLANT	116.0	-	166.0
STRUCTURE	179.0	300.0 ⁽⁵⁾	168.0
GUIDANCE & CONTROL	105.0	90.0	110.0
COMPUTER & SEQUENCER	18.0	22.0	16.0
TELECOMMUNICATIONS	100.0	87.0	100.0
THERMAL CONTROL	16.0	20.0	15.0
PYROTECHNICS	12.0	15.0	11.0
CABLING	49.0	60.0	46.0
POWER	200.0	30.0 ⁽⁶⁾	200.0
CONTINGENCIES	12.0	15.0	11.0
TOTAL DRY WEIGHT	812.0	1000.0 ⁽⁷⁾	762.0
INJECTED WEIGHT	1270.0 ⁽⁹⁾	-	1270.0 ⁽¹⁰⁾

Table II-4 Subsystem Sizing (concluded)

NOTES:

- (1) CONTAINS 2000 kg PROBE(S) WEIGHT, WITH 200 kgs ALLOCATED TO SCIENCE.
- (2) CONTAINS 2000 kg BALLOON WEIGHT, WITH 244 kgs ALLOCATED TO SCIENCE.
- (3) CONTAINS 2000 kg LANDER WEIGHT, WITH 180 kgs ALLOCATED TO SCIENCE.
- (4) CONTAINS 4100 kg LANDER(S) WEIGHT, WITH 400 kgs ALLOCATED TO SCIENCE.
- (5) CONTAINS 220 kg STRUCTURE WEIGHT PLUS 80 kg ADAPTER WEIGHT.
- (6) POWER SUPPLIED BY NEP SYSTEM, 30 kg ALLOCATED TO ADDITIONAL POWER CONDITIONING AND DISTRIBUTION EQUIPMENT.
- (7) DOES NOT INCLUDE PROPULSION INERTS OR PROPELLANT.
- (8) CONTAINS PROBE WEIGHT OF 1000 kg. TWO PROBES EACH WEIGHING 500 kg. EACH PROBE CONTAINS 38 kg OF SCIENCE. PROBES SIZED TO DESCEND TO 7.5 BARS IN NOMINAL ATMOSPHERE.
- (9) CONTAINS 342 kg PROBE WEIGHT, WITH 29 kg OF SCIENCE, PROBE SIZED TO DESCEND TO 7.0 BARS IN NOMINAL ATMOSPHERE.
- (10) CONTAINS 342 kg PROBE WEIGHT, WITH 29 kg OF SCIENCE. PROBE SIZED TO DESCEND TO 20.0 BARS.

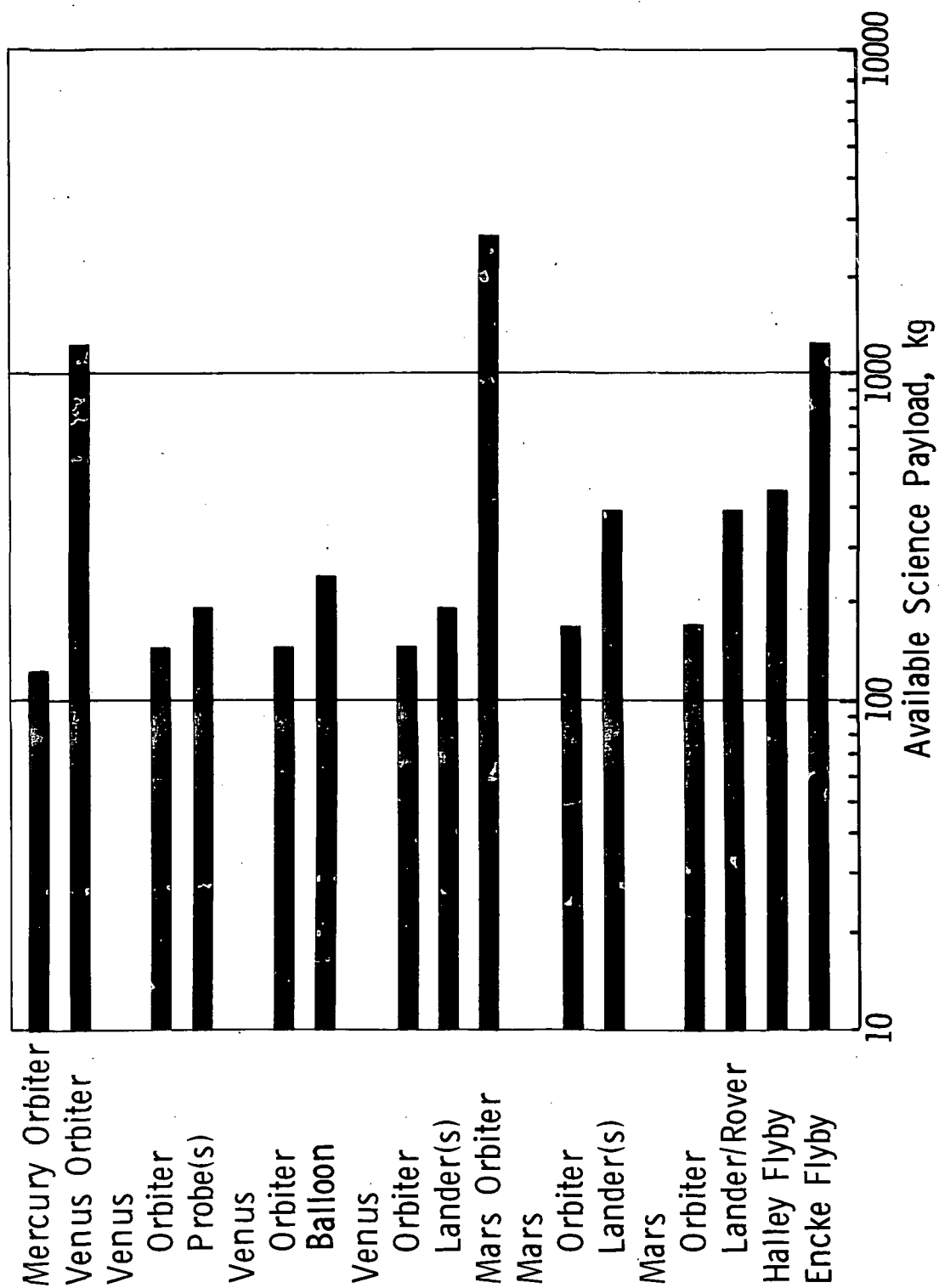


Figure II-7 Science Weight Available

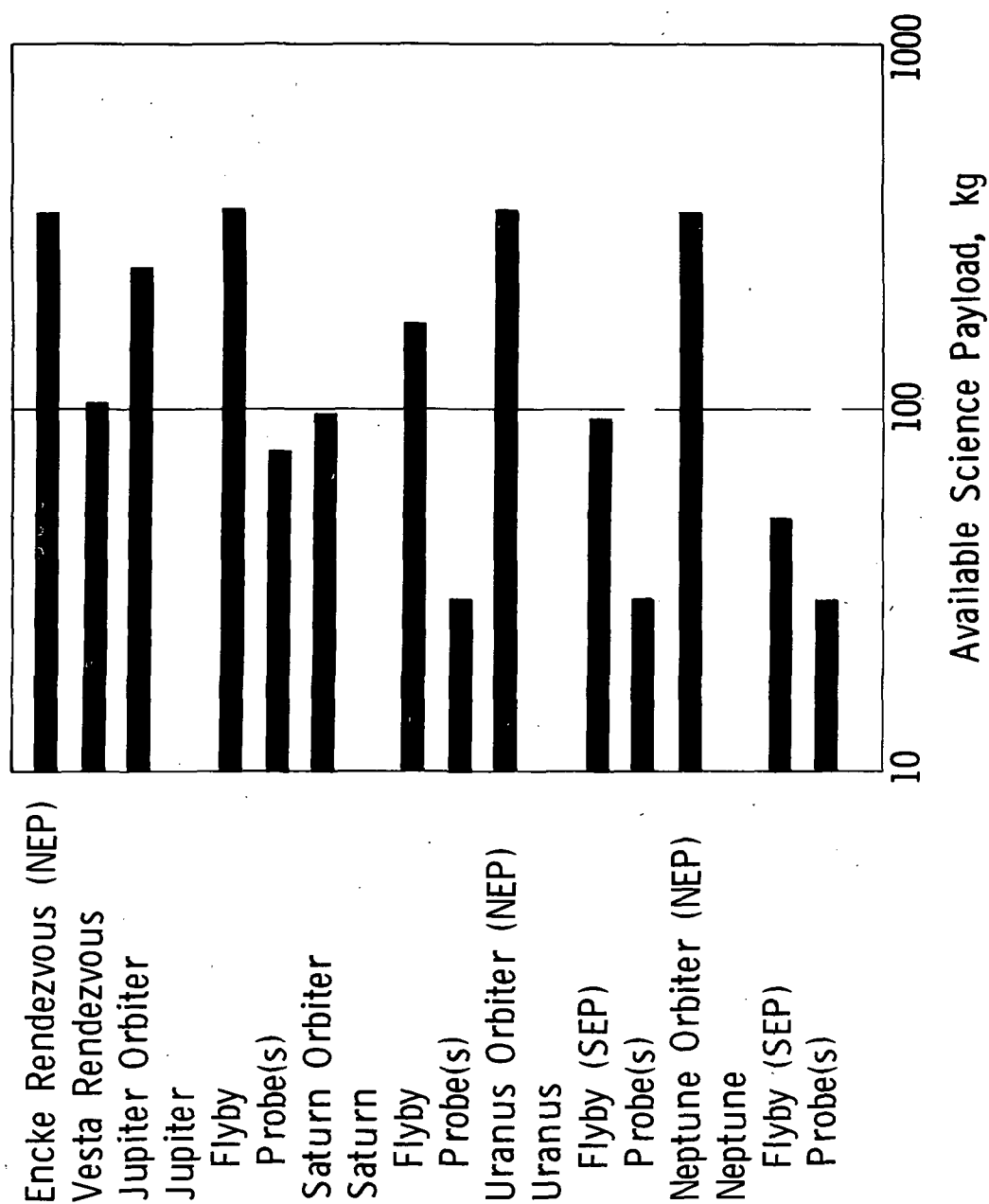


Figure II-7 Science Weight Available (concluded)

2. Communication Systems

In determining the need for on-board decision making it is important to know not only the round trip communication time (which puts a lower limit on the reaction time for Earth-based decisions) but also the available data rate (in bits/second), the on-board data storage capacity, and the total number of bits that can be returned to Earth during the mission. The data communication rates and capacities when compared with the rates and amounts of data generated by the sensors on the spacecraft determine the value of adaptive modes such as those that select the most interesting blocks of data for transmission.

To estimate the maximum data rates and volumes for the various missions, the following items were determined: representative communications subsystem technologies for future missions, expected mission durations, expected peak data rates, and corresponding maximum data volumes (product of data rate and mission times).

The basic assumptions necessary to guide the telecommunications survey are catalogued in Table II-5.

Table II-5 Communication Assumptions

400 Earth Day Nominal Orbiter Mission Duration
20% of Orbit Available for Earth Communications
Volumes Based on Projected Encounter Rates Defined
Adequate DSN Availability
Next Generation DSN for Multimegabit Reception
64M (210') Reception Dish
Probe Missions: 2 Hour Duration
Recorders Available with Compatible Recording/Relay Bandwidths
Times for Signal Synchronization and Lock Minimal

The 400 day mission permitted reasonable extrapolations of current subsystem reliability capability. The estimate of 20% of a planetary orbit being available for data relay was used to account for nominal Earth or solar occultations and DSN synchronization and lock up times. Encounter rates were based on the representative subsystem implementations discussed below and the planet-Earth ranges defined by typical trajectories. Those cases possessing very high data rate potential require the next generation DSN capability including X-band carrier operation and modification of the 500 KHz subcarrier limit.

a. Representative Subsystem Implementations - The missions were divided into three broad categories: a) orbiters and flybys, b) landers, and c) probes. Based on total spacecraft weight realms indicated by Mariner, Advanced Mariner, MVM, MJS, and Pioneer F&G programs representative communications subsystems were allocated to a selected set of spacecraft weight realm classes. The corresponding subsystems are summarized in Table II-3.

Orbiters and flybys incorporate anticipated advanced Mariner class hardware with an X-band carrier. Therefore spacecraft attitude pointing stability is assumed to be typically on the order of half of the typical HPBW of antennas to minimize pointing losses. Maximum radiated RF power was constrained to 20 watts (CW) and maximum antenna diameter to 3.7 meters (12 feet). Data signal-to-noise ratio as required for convolutional coding is incorporated with one-way doppler tracking techniques. No degradation for the wide range of doppler offset uncertainties recognized over all missions is singled out. That is, all data rate extrapolations were based on planet-Earth range for a particular communications configuration. The basic design control table was extrapolated from actual available MJS class performance expectations.

The Mars and Venus landers employ Viking lander class technology with antennas allocated based on atmosphere and entry condition differences.

Planetary probes operate with an L-band carrier to cope with expected atmospheres and tracking problems. Probe performances were taken from current studies of planetary probe missions.

b. Potential Data Rates Over All Missions - Peak available data rate performance curves versus planet-Earth distance in astronomical units (AU) are included as Figures II-8 and II-9. These performance curves were defined on the basis of currently available proposed MJS designs incorporating X-band carrier frequency operation.

Table II-6 shows anticipated data rates for all the mission options considered.

Data rate established, a determination of expected maximum data volume is accomplished by the product of data rate and typical mission duration. In order to specify a maximum data volume, encounter distance bit rates and mission durations allocated under the assumptions previously discussed were used to form the entries in Table II-7. Also included in the table is the orbiter mission time used for the total data volume calculation. The right hand column of the table presents the data volume determined by this process.

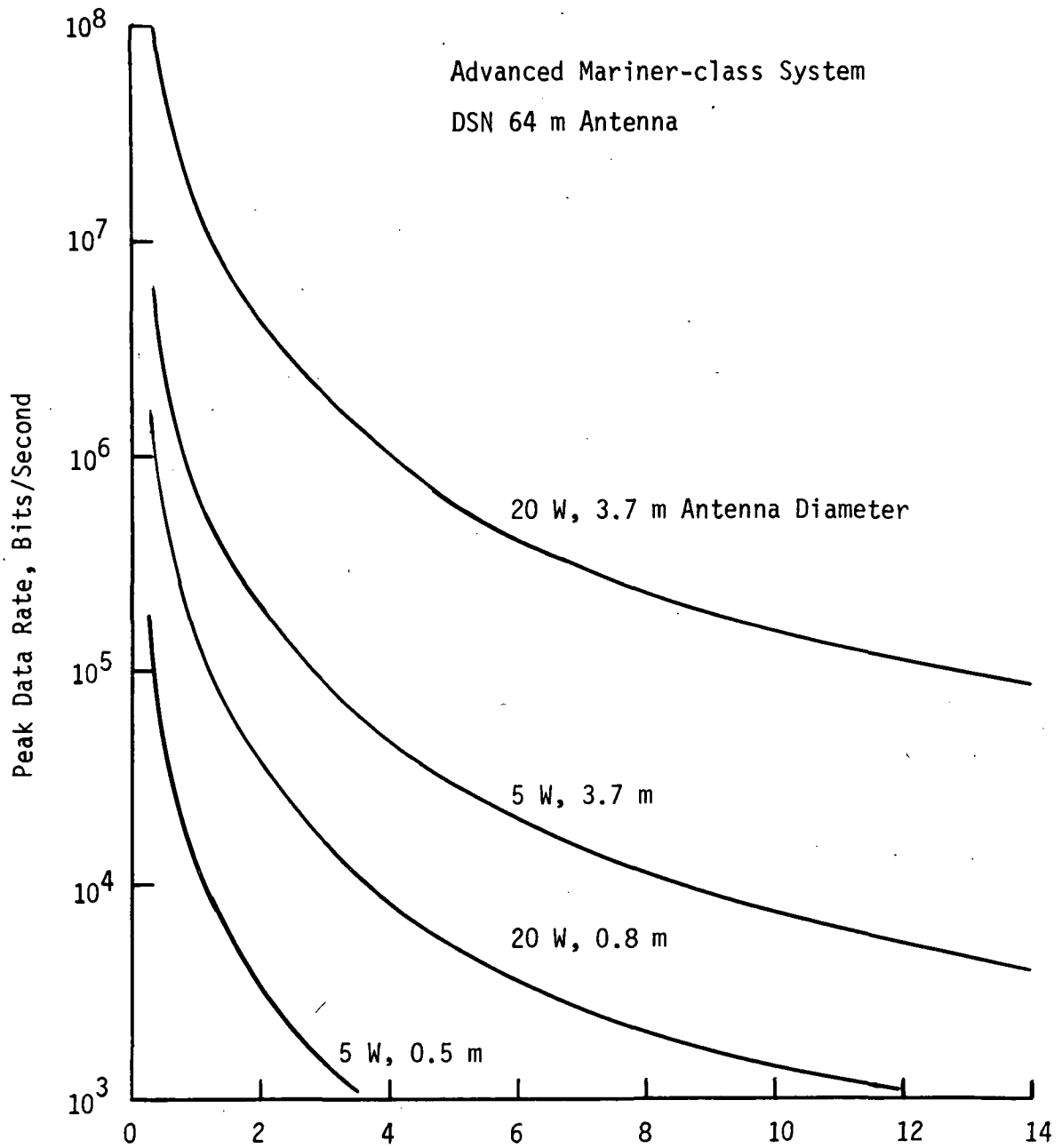


Figure II-8 Communication Performance to 14 AU

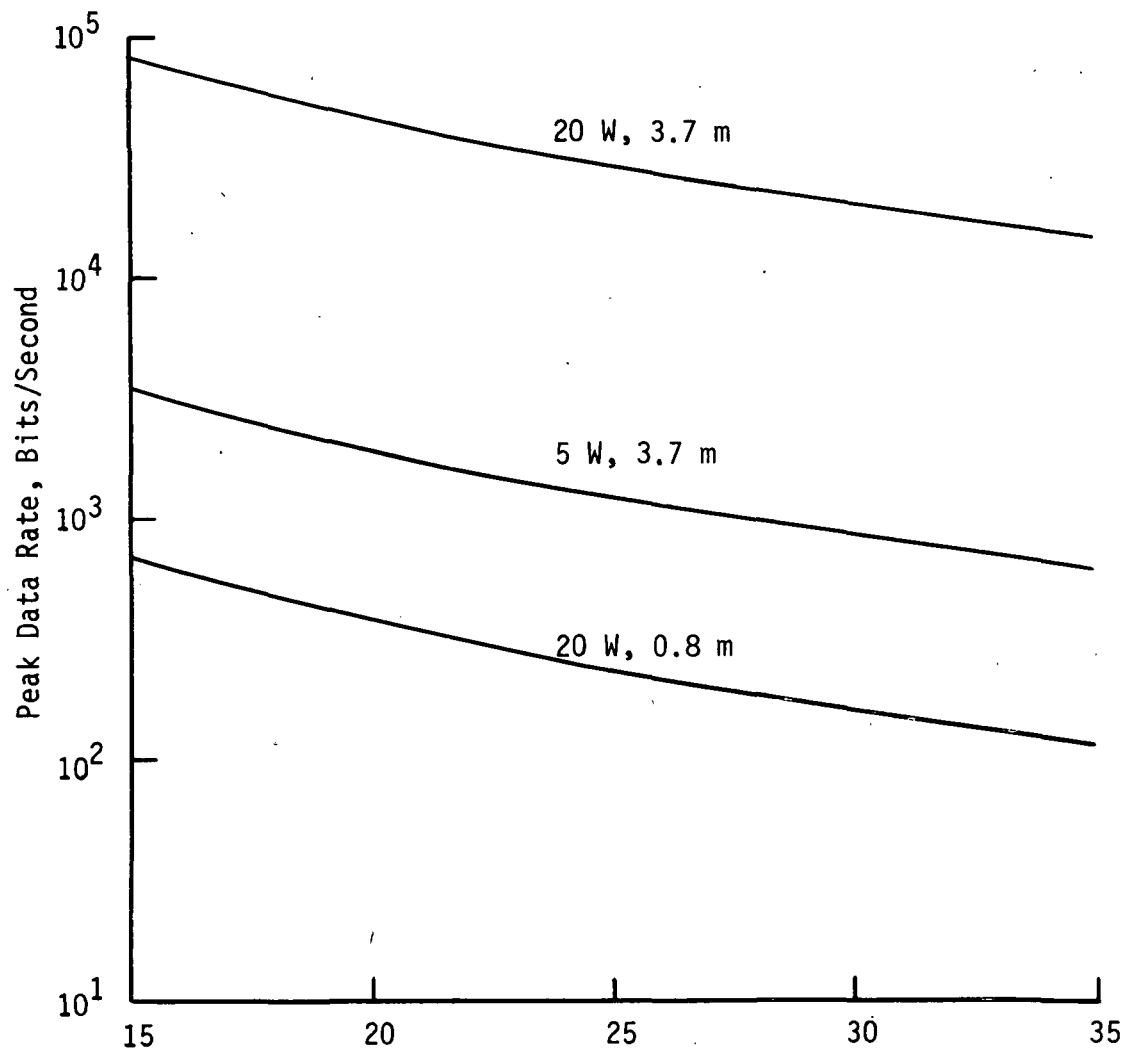


Figure II-9 Communication Performance Beyond 14 AU

Table II-6 Peak Available Data Rates

Mission	System	Bits Per Second		
		Maximum	Minimum	Encounter
1. Mercury Orbiter	20W/3.7m	13.5×10^6	1.6×10^6	3.8×10^6
2. Venus Orbiter	20W/3.7m	3.7×10^7	1.1×10^6	3.2×10^7
3. Venus Probe	20W/3.7m - Orbiter	3.7×10^7	1.1×10^6	3.2×10^7
	5W/.5m - Probe to Earth	1.5×10^5	4.5×10^3	1.2×10^5
4. Venus Balloon	20W/3.7m - Orbiter	3.7×10^7	1.1×10^6	3.2×10^7
	5W/.5m - Balloon to Earth	1.5×10^5	3×10^4	1.2×10^5
5. Venus Lander	5W/.5m - Lander to Earth	1.5×10^5	4.5×10^3	1.2×10^5
6. Mars Orbiter	20W/3.7m	13.5×10^7	4.7×10^5	3.4×10^6
7. Mars Lander	20W/3.7m - Orbiter	13.5×10^7	4.7×10^5	3.4×10^6
	20W/.8m - Lander to Earth	6×10^5	2.1×10^4	1.03×10^5
8. Mars Lander/ Medium Rover	20W/.8m - Lander to Earth	6×10^5	2.1×10^4	1.03×10^5
	Rover/Lander Relay	16×10^3	1	-----
9. Jupiter Orbiter	20W/3.7m	2.2×10^5	8×10^4	1.15×10^5
10. Jupiter Flyby/ Probe	20W/3.7m	2.2×10^5	1.15×10^5	1.15×10^5
	40W (L-Band) Probe to Flyby	1.33×10^3	1	1.33×10^3

Table II-6 Peak Available Data Rates (concluded)

Mission	System	Bits Per Second		
		Maximum	Minimum	Encounter
11. Saturn Orbiter	20W/3.7m	5.3×10^4	2.8×10^4	3.8×10^4
12. Saturn Flyby/ Probe	20W/3.7m 40W (L-Band) Probe to Flyby	5.3×10^4 1.33×10^3	3.8×10^4 1	3.8×10^4 1.33×10^3
13. Uranus Orbiter	5W/3.7m	3.1×10^3	2×10^3	2.5×10^3
14. Uranus Flyby/ Probe	20W/3.7m 40W (L-Band) Probe to Flyby	1.2×10^4 1.53×10^3	9×10^3 1	9×10^3 1.53×10^3
15. Neptune Orbiter	5W/3.7m	1.05×10^3	$.9 \times 10^3$	1×10^3
16. Neptune Flyby/ Probe	20W/3.7m 40W (L-Band) Probe to Flyby	4.1×10^3 1.33×10^3	3.6×10^3 1	4×10^3 1.33×10^3
17. Halley Flyby	20W/3.7m	1.5×10^6		
18. Encke Flyby	20W/3.7m	2×10^6		
19. Encke Rendezvous	5W/3.7m	5.2×10^5		
20. Vesta Rendezvous	20W/3.7m	2.8×10^6	2.5×10^5	8×10^5

Table II-7 Data Volumes

Mission	Peak Data Rate (Bits/sec)	Orbit/Mission Time (Sec)	Time (Hrs)	Number Orbits	Maximum Data Volume (Bits)
1. Mercury Orbiter	3.8×10^6	2.16×10^5	60	160	2.63×10^{13}
2. Venus Orbiter	3.2×10^7	9.72×10^3	2.7	3555	2.2×10^{14}
3. Venus Flyby Probe	3.2×10^7 1.2×10^5	2.94×10^6 7.2×10^3	81.7 2		9.41×10^{13} 8.6×10^8
4. Venus Orbiter Balloon	3.2×10^7 1.2×10^5	1.23×10^5 5.2×10^6	3.45 1440	3555	2.19×10^{15} 1.2×10^{11}
5. Venus Orbiter Lander	3.2×10^7 1.2×10^5	1.23×10^5 5.4×10^3	3.45 1.5	3555	2.19×10^{15} 6.5×10^8
6. Mars Orbiter	3.4×10^6	8.85×10^4	24.6	390	2.35×10^{13}
7. Mars Orbiter Lander	3.4×10^6 1.03×10^5	8.85×10^4 1.8×10^4	24.6 5	390 390	2.35×10^{13} 7.2×10^{11}
8. Mars Orbiter Lander Medium Rover	3.4×10^6 1.03×10^5 16×10^3	8.85×10^4 1.8×10^4 Continuous	24.6 5	390 390 390	2.35×10^{13} 6.92×10^{11} 5.54×10^{11} (100%)
9. Jupiter Orbiter	1.15×10^5	1.73×10^6	480	20	8×10^{11}
10. Jupiter Flyby Probe	1.15×10^5 1.33×10^3	2.11×10^6 7.2×10^3	586 2		2.42×10^{11} 9.6×10^6

Table II-7 Data Volumes (concluded)

Mission	Peak Data Rate (Bits/sec)	Data Volumes		Number Orbits	Maximum Data Volume (Bits)
		Orbit/Mission (Sec)	Time (Hrs)		
10. Jupiter Flyby Probe	1.15×10^5 1.33×10^3	2.11×10^6 7.2×10^3	586 2		2.42×10^{11} 9.6×10^6
11. Saturn Orbiter	3.8×10^4	7.69×10^6	2136	4.45	2.6×10^{11}
12. Saturn Flyby Probe	3.8×10^4 1.53×10^3	7.56×10^5 7.2×10^3	210 2		1.1×10^7
13. Uranus Orbiter	2.5×10^3	2.25×10^6	624	15.4	1.735×10^{10}
14. Uranus Flyby Probe	9×10^3 1.53×10^3	3.96×10^5 7.2×10^3	110 2		3.56×10^8 1.1×10^7
15. Neptune Orbiter	1.0×10^3	1.9×10^6	528	18.2	6.9×10^9
16. Neptune Flyby	4×10^3	3.67×10^5	102		1.5×10^9
17. Halley Flyby	1.5×10^6	3.6×10^4	10		3×10^{10}
18. Encke Flyby	2×10^6	2.78×10^4	8		3×10^{10}
19. Encke Rendezvous	5×10^5	8.6×10^6	2400		8.6×10^{11}
20. Vesta Rendezvous	8×10^5	8.6×10^6	2400		1.2×10^{12}

III. ADAPTABILITY

This chapter discusses adaptability in general and then shows how it applies to the various missions. Section A considers briefly how the need for adaptability depends on the limitations of the mission subsystems, the required reaction times, and the payload. Section B describes the characteristics of the data input, output, storage and processing that will have to be done to make a system adapt.

Specific modes of adaptability are described in Section C with emphasis on characteristics that will be similar on various missions.

A. NEED FOR ADAPTABILITY AND ONBOARD ARTIFICIAL INTELLIGENCE

Onboard artificial intelligence (AI) cannot be justified unless two conditions are met: (1) performance is improved, and (2) the required logical operations can not be done more cheaply on Earth.

The first condition implies that there is at least one bottleneck in getting meaningful scientific data to the ground that by being selective, the AI system can improve the quality or quantity of data. Some of the kinds of bottlenecks that limit solar system exploration are listed here:

- . sensors can not be activated all the time because of power or lifetime limitations.
- . sensors can not scan the target fast enough. An IR or UV sensor or a narrow angle camera can not cover the face of a planet during one pass.
- . sample preparation is slow or costly in power. X-ray diffraction samples must be reduced to a fine powder.
- . a rover can not move fast enough to adequately explore the terrain during the mission.
- . expendables, as for a biological assay, are limited so that very few trials are possible.
- . data storage is limited.
- . the communication link limits the amount of data that can be transmitted to Earth.

The second condition, that logical operations can not be done more cheaply on Earth, is satisfied if the greatest reaction time that can be tolerated is less than the round trip communication time. The tolerable reaction time may be determined by the total mission time (as with a flyby or an atmospheric probe), it may depend on the duration of phenomena such as storms or quakes, or it may depend on the need for a very

large number of successive decisions within a fairly long mission. An example of the last case is the requirement to provide frequent commands to a rover to keep it moving safely.

B. DESCRIPTION OF ADAPTIVE MODES

In compiling lists of ways that solar system exploration missions can be made adaptive, it was found that most of them could be applied to more than one mission. Furthermore, the same themes kept reappearing with different phenomena, instruments, and actions. In an attempt to systematize the discussions of adaptive modes, they have been classified according to their functions. As with all classifications of real things, it is sometimes difficult to make a good assignment to a class, but classifying the modes makes them easier to talk about and may help in finding additional applications.

The modes compiled in this study were contributed by many people including our Science Panel. Some that were considered trivial or ineffective were culled out. Of the remainder, some will be of marginal advantage on missions with large data storage and transmission capability, and others are somewhat speculative but may find application on future missions.

The applications of adaptive modes to each of the various missions are enumerated at the end in Chapter IV. Computational requirements for some of the modes will be briefly stated in this section. Section III-C gives an assessment of the computer requirements based largely on programs that have been written.

1. Image Feature Extraction

This mode will detect something of interest in the field of a relatively wide angle imager and will direct the pointing of another sensor so that more detailed data can be obtained. The second sensor may be a narrow angle camera, an IR or UV radiometer, or a sampling boom on a rover.

Targets can be of many types. For Jupiter orbiters, the great red spot will have high priority, but some smaller spots have been observed from Earth, and it is likely that there are at least occasional spots too small for terrestrial telescopes to detect. Because of their mobility, they will have to be located and observed in detail during one orbital pass, and there will be no time for decision making on Earth.

Other targets on cloudy planets include holes or thin spots in the clouds, clouds of unusual color (the particular color of interest can be specified from Earth after the first pictures are analyzed), 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. 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.

Shadows or silhouettes on the clouds can lead to discovery of small close satellites if they can be tracked.

It is possible that sunrise on Mercury causes a little outgassing. Feature extraction can be used to keep a UV sensor accurately pointed over the bright side of the terminator to detect scattering from any such emissions.

Jupiter orbiters (and orbiters of Venus, Saturn, Uranus, and Neptune) will have sufficient lifetime for their programs to be modified by the scientific team on Earth to take advantage of information gained from the early images. When interesting and unexpected transient features are found by the human team, criteria for onboard identification can be transmitted to the orbiter so that similar phenomena on later passes will be detected and subjected to detailed examination by the narrow angle sensors.

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 requires only a few words of instruction. More words are added if the search is to be limited to some area such as the illuminated part of a planet. 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 Appendix E of Volume III of this report.

Color in the scene can also be exploited. A red spot will be bright with a red filter and dark with a blue one. If a single filter gives adequate discrimination, the program is, of course, the same as the one mentioned above. However, if it is necessary to use data from 2 or 3 images in different colors to distinguish the feature from the background, the task is more complicated. If the imaging system detects all colors simultaneously, or if the scene does not change during the time

needed to make pictures with various filters, the added complexity is modest. The maximum and minimum brightnesses can be specified for each filter, or the ratios of the brightnesses with the various filters can be used as criteria. If the colors are detected in successive frames, as with a filter wheel, and if the image motion is rapid, as may be the case for a planetary orbiter, the frames will not register perfectly and routines for registration and rectification may be necessary.

In many scenes, the illumination changes greatly across the picture. Absolute brightnesses are then poor criteria for distinguishing features, and it is much better to use brightness relative to nearby regions. A simple criterion is the difference between the brightness of a particular pixel and some weighted average brightness of preceding and following pixels in the same line. If the brightness level is to be compared with an average taken over pixels in neighboring lines, then these lines must be held in the fast memory.

Texture can be used as a criterion instead of or in addition to brightness and color. Storms on Jupiter might be characterized by cloud patterns with a dominant spatial frequency band. The pictures taken on an early orbital pass could be analyzed on Earth and instructions could be sent to the orbiter to program a digital filter sensitive to that band so that if there is another similar storm it will be detected and imaged at higher resolution and its temperature will be measured with an IR sensor. If the filtering is done in one dimension along a scan line, the filtering is simple. If two-dimensional filtering is needed, it is necessary to combine data from many lines, and the computer's task is substantially greater.

2. Guidance and Navigation

This mode guides a vehicle by using data gathered by the imaging system or other sensors. The objective may be to land in a safe place on a planet, to reach a preselected point, to steer a rover past an obstacle, or to get a close look at a comet without too much danger from debris.

Martin Marietta's Planetary Landing Site Selection System (PLSSS)* is designed to be applied to a lander such as Viking. It monitors the amount of detail in each of 9 regions of an image of the planetary surface during descent. Since time of day is chosen so that surface irregularities give long shadows, the safest area is likely to be the one with least detail, and that is where the vehicle is guided. The PLSSS would be valuable for asteroid touch-down as well as Mars landing.

For comet flybys, the imaging system or an optical scanner could detect the dust cloud surrounding the comet and modify the trajectory to pass as closely as possible without unacceptable risks. Discrimination between dust and the gaseous coma could be based on the difference in the spectra of light scattered by dust particles of wave-length size and greater (Mie scattering) and that scattered by molecules (Rayleigh scattering).

The imaging system could also provide data for targeting a suicide probe on the cometary nucleus.

A planetary rover needs an automatic hazard avoidance system if it is to be trusted to go more than a few meters without

* Roger T. Schappell and Gail R. Johnson: *Experimental and Simulation Study Results on the Development of a Planetary Landing Site Selection System*. AIAA Guidance and Control Conference, Stanford, Calif. AIAA Paper No. 72-868, Aug. 14-16, 1972.

guidance from Earth. If it depends on a stationary lander, it also needs a control to keep it from wandering out of range of the radio link to the lander. This mode can use the RF signal strength as an input and make the rover retrace its path when the signal drops below some threshold.

A Mars rover could detect water vapor or other interesting gases and follow the scent upwind to the position of greatest concentration. By using a clinometer as a data source, it could direct the rover to the top of a hill or the bottom of a depression.

3. Transient and Transition Detection

Transients are more or less rapid changes in time, and transitions are changes that are observed as a vehicle moves from one region to another. There are many ways an exploration system can respond to these changes.

A Mercury orbiter can watch for solar flares (as evidenced by increased x-rays, for instance) and increase the resolution on an x-ray fluorescence spectrometer.

A Venus balloon can monitor the surface below with a radar altimeter and turn on a radar mapper when it is over a very high or low place or where interesting terrain is indicated by rapid variations in elevation. A probe might be dropped over a very low point. The controller can also detect sunset at the balloon is carried across the terminator by the wind. It will then turn off the experiments, such as imaging and the sunlight monitor that are useful only on the sunny side. When the Earth sets it will turn off the transmitter and start recording data until communications are again established.

On a flyby of a comet or planet, radio noise may be detected by a receiver that scans a wide frequency band. The receiver can then be directed to stop its scan and track the source. After some reasonable time it should revert to scanning the spectrum to see if other frequencies are present.

A Jupiter orbiter can listen for bursts of decametric radiation and record them for transmission to Earth.

During a cometary rendezvous mission, pieces of the nucleus may be ejected by the pressure of gas generated by solar heating. A motion detector could give the signal to direct the imaging system to get pictures as the fragments leave the comet. If the velocities are low enough it may even be possible to capture some of the nuclear material.

The planetary atmospheres can be observed with increased data rate in the x-ray and gamma-ray spectra whenever solar flares have been detected.

Planetary probes, including the Venus balloon, can take atmospheric samples when local electrical activity is high to detect discharge-produced molecules. Some of the instruments on the atmospheric probe are useful only in certain altitude ranges, ion detectors in the ionosphere for instance. A controller using the instrumental outputs can turn experiments on and off to save power and communication capacity without losing valid data.

On Mars typical transitions detected by a rover would be a change in surface albedo indicating a change in soil or the edge of the frost cover, or a change in the required propulsive force indicating a change in surface properties or slope. Appropriate action includes taking samples and making pictures.

The Mars lander can detect clouds either with a skylight monitor or by using the imager to scan the sky in a coarse grid. When a cloud is detected it can be imaged. When the communication and data storage systems are saturated with pictures, further images can be analyzed to yield the direction of the center of the cloud and its angular area as a function of time until it disappears. If a rover with imaging is included in the mission, wide-base stereo pictures can be taken so that absolute cloud height and size can be deduced by the scientific team.

Large earthquakes sometimes produce flashes of light. When large quakes are detected at night on Mars, the imaging system or other light sensors can be activated on the chance of detecting an analogous phenomenon.

If lightning is detected on Mars (it may be generated by the dust storms) it would be interesting to listen for thunder. In the absence of a microphone, the seismometer would stand a good chance of picking up the acoustic vibrations coupled to the lander. On the chance that auroras may be seen on Mars, the imaging instruments could be directed toward the polar skies on nights when solar flares are known to be bombarding the planet.

On a cometary flyby that includes a transit of the Sun (or an occultation, depending on the relative angular sizes of comet and Sun), the controller can detect the moment of minimum sunlight to trigger the imaging system to get the best silhouette of the comet's nucleus.

4. Controller

The controller mode makes more or less simple adjustments to optimize some operation. Exposure control of any imaging system is an example. In a scanning camera, such as the Viking Lander

facsimile camera, it may be feasible to vary the scan rate according to the brightness of the part of the scene being scanned. This will reduce the time needed to get a picture and still assure that enough photons are received from the darker regions. The brightness level for each pixel is computed as the number of photons received divided by the time spent on the pixel.

If close-up pictures of the planetary surface are to be taken from a rover, some means of automatic focusing is required. The focusing becomes rapidly more critical as the magnification increases. Appendix B describes a self-focusing microscope conceived under one of our overhead tasks. The control functions could be supplied by the central computer on a lander or rover or could be designed with special purpose hardware.

A controller on a Venus lander can monitor the output of the various data sources and turn off instruments when their data become uninteresting either because the instrument is failing from heat or because the measured quantity shows no variety as, for instance, the imaging in thick dust or fog. The reduction in power dissipation will reduce the heat load and prolong the life of the lander.

A sample drill for a planetary lander needs controls to avoid sticking and overheating and to get efficient operation. Variables to be controlled include torque, vertical force, and total mechanical power input. A simple strategy to avoid sticking is to lift the drill a few centimeters when the torque exceeds a safe level and then lower it slowly to clear the cuttings from the bore.

A balloon in the atmosphere of Venus can use a controller to help it maintain its altitude with a minimum of make-up gas. The balloon will be of the hyperpressure type that has a strong

envelope to maintain nearly constant volume of gas over some range of pressures. If the Sun heats the balloon too much, the pressure exceeds the limit of safety and gas is vented. If it cools too much by radiation, the volume decreases and the balloon may descend out of control unless more gas can be generated fast enough. A good control system can predict requirements from measured values of radiation, ambient temperature and pressure, and the temperature and pressure of the flotation gas. It will turn on the gas generator only when it is needed and will prolong the life of the balloon.

The gas chromatograph separates gases according to their mobility in a capillary with a special surface treatment. The gases of higher molecular weight are generally slower. It is not known in advance what degree of molecular complexity will be found, but it seems certain that all degrees of complexity up to the maximum will exist without appreciable gaps. The strategy for using the gas chromatograph, then, is to continue detection with one batch of gas until nothing more comes out of the capillary for a certain time. The run is then terminated by the controller and another batch is started.

A problem in designing missions to probe the atmospheres of the outer planets is that there is no good way of predicting the atmosphere's attenuation of the radio waves that will carry the data from probe to flyby spacecraft for relay to Earth. If we design for too little attenuation, all the data will be lost below a certain altitude. If we design for too much attenuation, our data rates will be much lower than necessary, and we will get less information than we might have. The major unknown factor in attenuation is the ammonia concentration. A controller on the probe could monitor this and adjust the transmission to the

maximum safe bit rate. If there is a two-way link between probe and spacecraft, a much more precise control can be based on received signal strength (or error rate if error control coding is used).

An important objective of any cometary mission is to find the size and shape of the nucleus. It will be difficult to photograph the nucleus of Halley's comet on the flyby because the coma will be well developed and will tend to mask the nucleus. The brightness of the coma is largely due to line emissions characteristics of the gases it contains. If the gases in the coma were known, it would be possible to design filters to selectively reduce its brightness. Unfortunately, no good spectroscopic observations of Halley have been made, and the coma will not be developed before the flyby vehicle must be launched. However, an onboard controller could examine the spectrum during approach and choose a combination of filters to optimize the image of the nucleus.

Controllers can contribute to mission safety as well as performance. Suppose, for instance, that a Venus balloon lowers a sonde on a long thin cable to explore the atmosphere a kilometer or more below. Violent storms that could tangle the cable could be detected by a controller that monitors the balloon altitude as a function of time. When the balloon starts ascending or descending sharply, the sonde should be retrieved.

Outer planet probes will pass through regions of intense radiation. Certain instruments such as multiplier phototubes will be damaged if they are powered at that time. A controller can monitor the radiation and make sure that sensitive equipment is protected.

5. Sample and Data Screening

The screen mode throws out uninteresting material, either data or samples.

Consider a rover on Mars gathering samples from the surface for analysis by x-ray diffraction in the stationary lander. The rover is limited in the number of samples it can retrieve, and the x-ray diffraction analysis requires sample preparation by grinding to a fine powder and it uses a relatively long counting time. It is therefore advantageous to screen the samples either in place on the surface or on the rover to eliminate the ones that are not interesting.

Of course, a criterion of interest must be specified. A simple and effective criterion is the difference between the new sample and all those that have previously been examined in detail. Typical preliminary measurements that are useful for screening geological specimens are albedo values in several bands of the visible and IR spectra and the strengths of lines in the x-ray fluorescence spectrum that correspond to certain elements. A set of N such quantities can be conveniently treated as an N -dimensional vector. A distance between two samples in N -space can then be computed as the square root of the sum of the squares of the differences of the N pairs of measured values.

The new sample will be accepted for detailed analysis if it is more than some specified threshold distance from all previously analyzed samples. Appendix D in Volume III describes an algorithm for sample screening and shows some results when it is applied to x-ray fluorescence data.

Data screening is in some ways similar to data compression, but it is more apt to decide whether large blocks of data are

worth obtaining and transmitting rather than operating on a few words at a time as data compressors usually do.

On a Venus lander it will be desirable to get pictures of the landscape, but the transparency of the atmosphere will be hard to predict.

The screen can control the imager to direct it only where detail can be discerned. For instance the scan can be started from the lowest angle and continued upward until the brightness levels of the pixels become uniform indicating that the landscape is obscured by haze. The scan should then be returned to the bottom and the next vertical line traced. The same strategy can be followed in a clear atmosphere such as that of Mars between dust storms. In this case, the scan will be stopped after a few pixels of sky have been detected above the horizon.

Screen will be installed on Viking to increase the bit rate on the seismometer when an event has been detected. An improvement on this scheme (which will not be included in the Viking system) would be to raise the event threshold when the wind blows to reduce triggering caused by motion of the lander.

C. COMPUTATIONAL REQUIREMENTS

The artificial intelligence (AI) needed for an adaptive system can be generally characterized in terms of input data, the processing that is required, data and program storage, and the type and amount of output.

The input may consist of a long stream of numbers all representing the same type of phenomenon. Examples are images, spectra and seismic data. The number of bits per datum is related to the precision of the measurements, and is typically 10 or fewer.

Another kind of input consists of simple data from many different sources. This is the kind of input that is used by a central controller to determine what actions are possible, required, and desired. Engineering status, environmental data, scientific measurements, ephemerides, times when actions were last performed, and commands from Earth may all be combined in making decisions.

Processing may involve few or many unit operations, and these may be repetitive or highly varied in type and sequence. Seeking a maximum or minimum, perhaps the brightest element in a picture or the coldest point in an IR scan, requires handling many data items, but the operations are very simple: read a new number, compare with a stored number, store the larger one together with its coordinates, and repeat until all data have been read. When processing like this must be done very rapidly, special purpose hardware may be the solution. This may be designed as a separate electronic component, or it may be incorporated in a general purpose computer as a hardwired subroutine. Large scale integration (LSI) makes it possible to put a moderately complex subroutine on a single chip. If this approach is used, the spacecraft computer

should be designed to accommodate several plug-in single chip modules that can be designed and modified for particular missions. When complicated arithmetic and logical routines are required, it is necessary to use a computer with stored programs.

Memory is used as a data buffer as well as to store instructions. An algorithm that analyzes images does not need much buffer if it does not involve relationships between pixels in different lines. However, if its task is to recognize an object that spans several lines, then it generally needs prompt access to several lines of data and must store them in the buffer.

The output of the computer may be characterized by the complexity and precision of each item and the number of frequency items. Typical outputs would be a decision to make a measurement, control signals to a sample collecting boom, propulsion and steering commands for a rover, or instructions on how to read out data for transmission to Earth.

These computational requirements are all determined in terms of the number of words of memory required to effect the particular operation, providing that a computer with excess memory is available. In some cases it may prove impractical to extend the computer memory, and in others there may be no computer at all. In these cases, special purpose logic circuitry such as shift registers, adders, etc. can be used for many purposes. When more flexibility is required, one of the central processors-on-a-chip computers could be employed with a minimal addition to the system weight and power requirements.

From the various possible instrument interactions of each of the planetary missions, adaptive modes which increase the science value were identified. These modes have been grouped into five functional classes; image feature extraction, guidance and control,

transient and transition detection, various controllers, and sample and data screening. Any given mode can be further classified according to the mathematical algorithm required to place it into effect. For example, the computer capability required to extract an image feature is a function of the type of feature.

In order to economically size the computer requirements for all the planetary missions, each individual mode was broken into a rather small number of computer routines which are not identified with the mode's functional purpose, but rather with the algorithms and procedural sequences which it requires. These computer routines are then broken into two classes; computational routines which perform special algorithms and connective structures which act as main programs. In general the connective structure reads in an input parameter, performs the indicated operations on it, makes the appropriate decisions and issues an output.

Table III-1 lists the number of computer words required for the various routines used to size the computer capability required for the planetary missions. A brief description of these routines is given below. Appendix C provides a much more detailed description including listings.

1. Evaluation of Simple Functions

Many of the adaptive modes identified require the calculation of some logical or numerical value to place them into effect, for example (logical): "Turn on instrument A if instrument B is on and instrument C is off." or (arithmetic): "What is the product of the rate of change of pressure divided by the rate of change of altitude and the inverse of the force of gravity?" The final use of this computed value has many possibilities.

The computer words required to evaluate such an expression is a function of the number of variables, and whether the variables are already stored in the computer memory or not. The number and type of operators also have a bearing on the computer requirements.

The evaluation of functions which contain exponential, logarithmic or trigonometric operators must be evaluated in an iterative manner by the use of a series, and therefore can not be sized with this approach.

2. Means of a Set of Data

Many adaptive modes require a discrete signal output when the mean of a set of data exceeds some preset value. This mean can be either the mean of the total set of data or the mean of recent values of the total (running mean). Figure III-1 shows how these two types of means are generated for a sample of input data and how they may be compared with a preset limit.

3. Variance of a Set of Data

Two types of variances are useful in the analysis of instrument data outputs. Again the statistics can cover the total set of data or just the recent values. Figure III-2 shows an example of a signal having a changing variance, but a constant mean. As can be seen, the running variance provides a more sharply defined signal output, but the variance of the total data is useful in comparing the surface roughness between two scenes for example.

4. Comparison of a Computed Value with a Limit

With this connective structure, one of the calculated values described above is compared with a preset value and a discrete output is generated. Figure III-1 showed this process when the calculated value was a running mean.

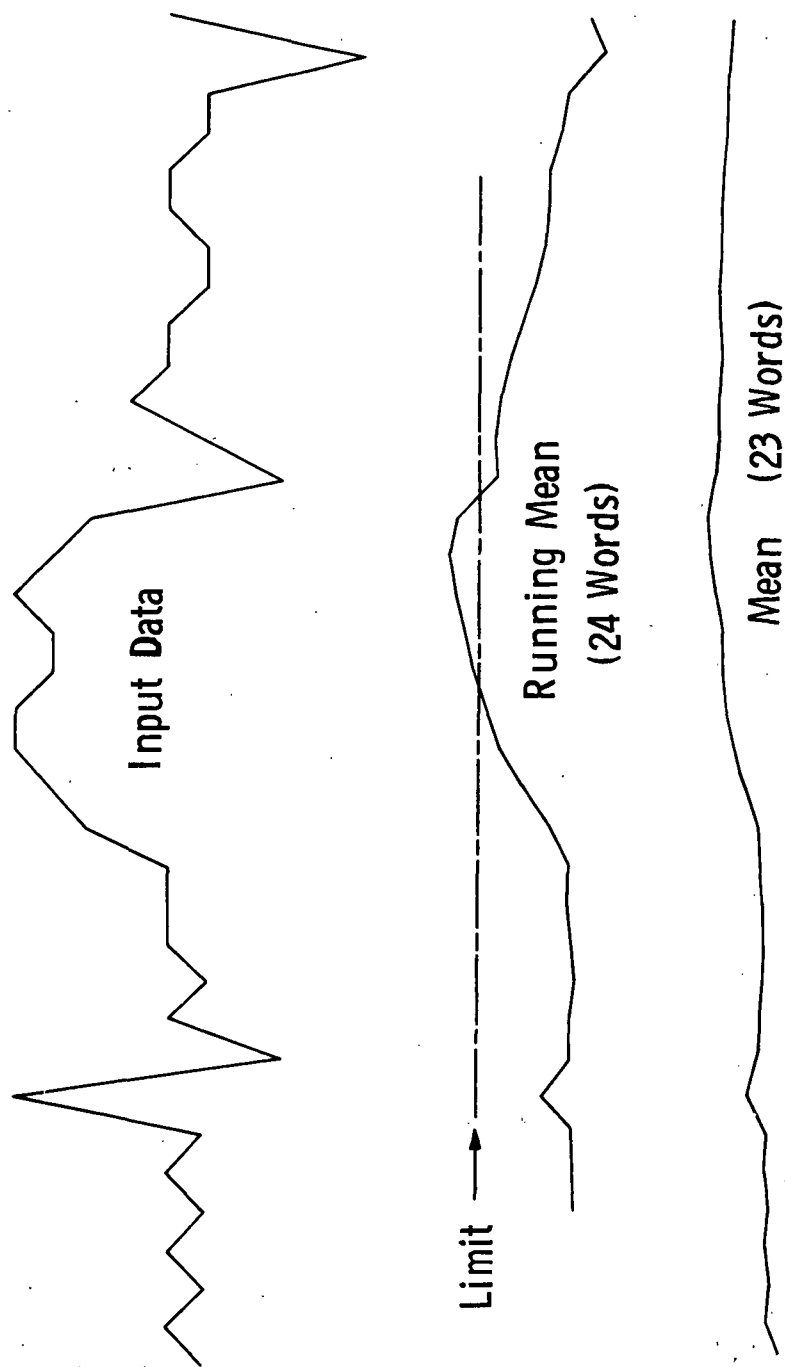


Figure III-1 Computational Routines - Mean

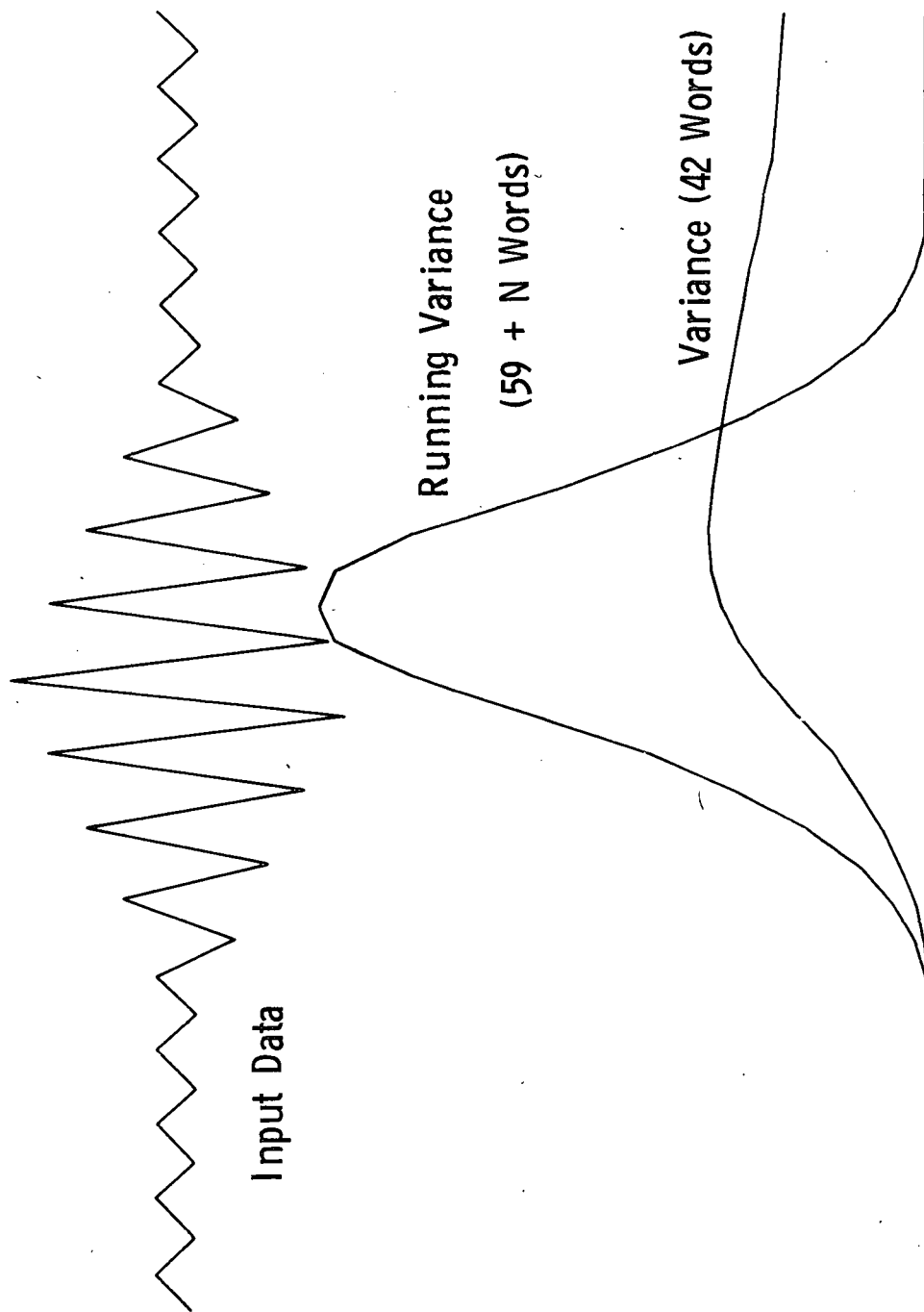


Figure III-2 Computational Routines - Variance

5. Comparison of the Difference Between Two Values

This routine compares the difference between two calculated values, for example, short and long term running means with a preset value to generate a discrete output. This routine is particularly valuable in extracting anomalies from an unpredictable background. Figure III-3 plots an example of the use of this routine when used with running means.

6. Fix a Two Dimensional Position

With the aid of several of the preceding routines this connective structure is able to define the position of a two dimensional anomaly, for instance, in a TV scene, without storing the total scene.

7. Computer Requirements for Adaptive Modes

Table III-1 summarizes the computer capability required for each of the sizing routines. In addition, Table III-2 lists the identified adaptive modes along with a breakdown of the number of computer words which would be required to place them into effect. The mission types are grouped so that missions having similar characteristics, such as sensors used and mission duration, are placed together even if the associated planets are not. The functional type of adaptive mode is also listed.

In some cases these building block routines are insufficient for the purpose and in these cases, other programs which can accomplish the task have been converted from large computer Fortran programming to equivalent Viking GCSC words.

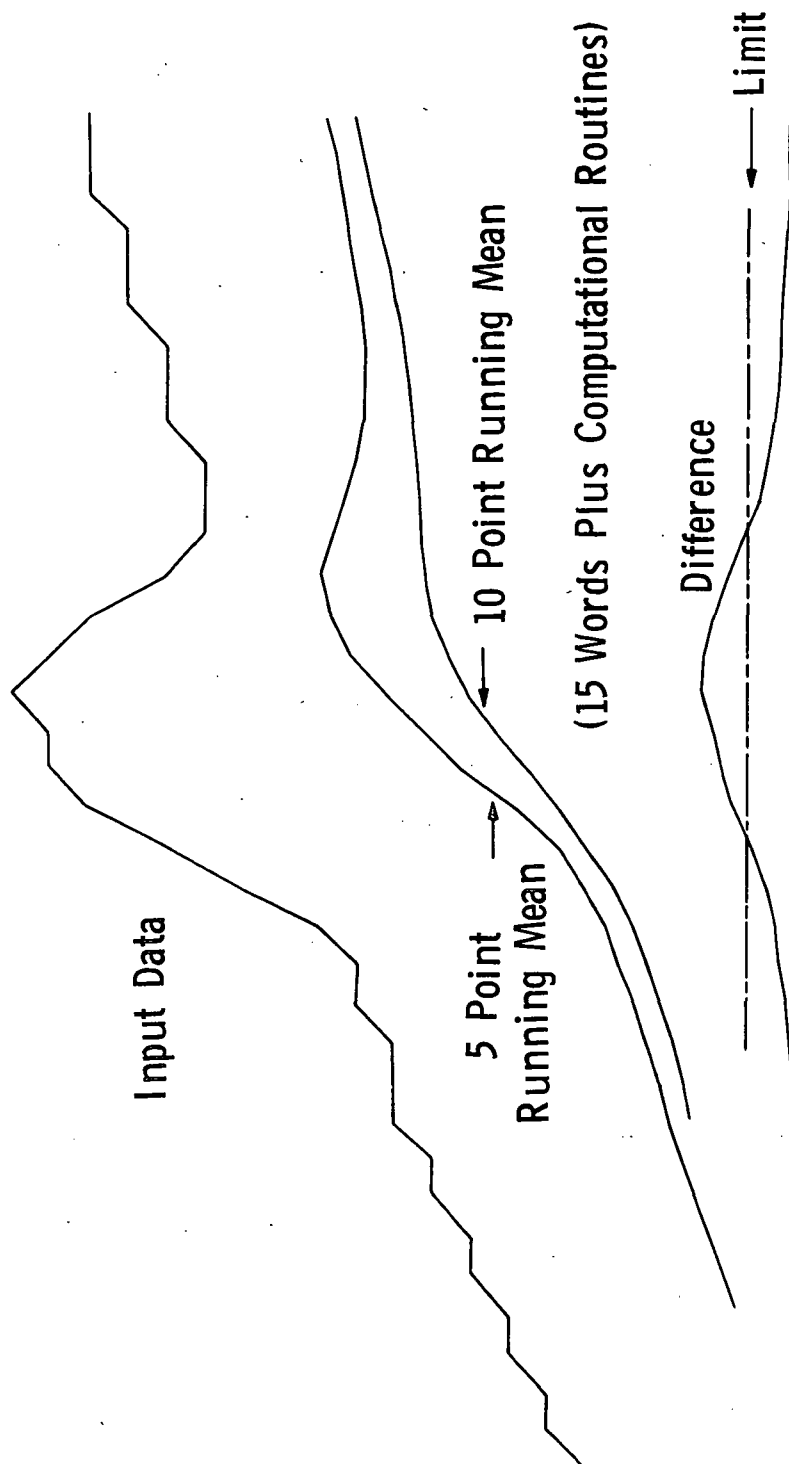


Figure III-3 Connective Structures - Compare Difference with Limit

Table III-1 Summary of Sizing Routines

	<u>Required Words</u>
Computational	
Simple Functions	
V = number of input variables	5V
S = number of stored variables	S
D = number of integer divisions	3D
M = number of integer multiplications	2M
Op = number of other operators	Op
Mean	23
Variance	42
Running Mean	24
Running Variance for N Samples	N + 59
Connective Structures	
Compare Value with Limit	14
Compare Difference with Limit	15
Fix Two Dimensional Position	105

Table III-2 Mission Adaptive Modes

Table III-2 Mission Adaptive Modes																	
MISSION ADAPTIVE MODES	FUNCTION	WORDS REQ'D	COMPUTATION										CONNECTIVE STRUCTURES				
			TOTAL	RUNNING		INPUT VARIABLE	DIVISION	MULTIPLICATION	OTHER OPERATORS	COMPARE VALUE WITH LIMIT	COMPARE DIFFERENCE WITH LIMIT	FIX TWO DIMENSIONAL POSITION					
				VARIANCE	MEAN												
															VARIANCE	MEAN	
1. <u>Mercury Orbiter and Asteroid Rendezvous</u>																	
a. <u>Process TV data to determine proper exposure in dark areas</u>	Controller	168															
b. <u>Monitor solar magnetic field to anticipate effects of solar flares</u>	Transient	38		24											14	15	105
c. <u>Track terminator to look for outgassing albedo changes or atmospheric changes</u>	Transient	55		24													
d. <u>Landing site selection (Asteroid landing)</u>	Guidance	2200															
e. <u>Track limb to look for clouds</u>	Transient	38		24											14		
f. <u>Direct TV with thermal mapper</u>	Feature Extraction	168		48												15	105
2. <u>Venus Balloon</u>																	
a. <u>Search for surface anomaly, signal for radar mapping or probe drop</u>	Transient	93		79											14		
b. <u>Control inflation gas generation by processing atmospheric temperature, pressure, superpressure and radiant flux</u>	Controller	45													14		

Table III-2 Mission Adaptive Modes (continued)

Table III-2 Mission Adaptive Modes (continued)															COMPUTATION				CONNECTIVE STRUCTURES		
MISSION		ADAPTIVE MODES	FUNCTION	WORDS REQ'D	COMPUTATION								CONNECTIVE STRUCTURES								
					TOTAL		RUNNING		INPUT VARIABLE				INCLUDES: Read input value, make specified comparison and provides output if comparison is outside limits								
					MEAN	VARIANCE	MEAN	VARIANCE	+	5	1	3	2	1	COMPARE VALUE WITH LIMIT	COMPARE DIFFERENCE WITH LIMIT	FIX TWO DIMENSIONAL POSITION				
2. Venus Balloon Con't					23	42	24	59		5	1	3	2	1	14	15	105				
c. Raise tethered probe when air is turbulent			Controller	35						10	3	4	1		14						
d. Stop transmission at Earth-set			Controller	38			24								14						
e. Turn on night instruments at sun-set			Controller	38			24								14						
f. Transmit TV only when detail is present			Data	93				79							14						
g. Perform life detection experiment when pre-established temperature, pressure and composition conditions are met.			Screening																		
h. Detect atmospheric anomalies in composition, temperature, transparency or particle size to signal data rate increase.			Controller	48					20	5			9		14						
			Transient	56											56						
3. Venus Lander																					
a. Cut off non-productive instruments			Controller	38			24								14						
b. Determine the direction of maximum and minimum contrast for optimum coverage of TV			* Feature Extraction	100					80						20	for storage and output					

III-

Table III-2 Mission Adaptive Modes (continued)

MISSION	ADAPTIVE MODES	FUNCTION	WORDS REQ'D	COMPUTATION										CONNECTIVE STRUCTURES		
				TOTAL	VARIANCE	MEAN	RUNNING		INPUT VARIABLE	STORED VARIABLE	DIVISION	MULTIPLICATION	OTHER OPERATORS	COMPARE VALUE WITH LIMIT	COMPARE DIFFERENCE WITH LIMIT	FIX TWO DIMENSIONAL POSITION
							VARIANCE	MEAN								
3.	Venus Lander Con't				23	42	24	59	5	1	3	2	1	14	15	105
	c. Switch attention to seismic event	Transient	38											14		
	d. Limit upward sweep of TV scan when detail ends.	Data Screening	83				69							14		
	e. Detect changes in atmospheric wind, dust, temperature and composition to signal emphasis change.															
	f. Detect changes in illumination and determine cause by TV scan	Transient	49						20	5	3	7		14		
	g. Detect chemical and physical differentiation in immediate vicinity of lander; signal dispatch of rover or reach out	Transient	168				48								15	105
	h. Detect Electric or sonic disturbances	Transition	49						20	5	3	7		14		
		Transient	68				48	5				1		14		
4.	Comet Flyby															
	a. Provide image motion compensation	Controller	168				48								15	105
	b. Provide adaptive filtering of spectral lines from coma gas to search for nucleus	Controller	70		42									14 + 14	to store maximum variance	

INCLUDES: Read input value, make specified comparison and provides output if comparison is outside limits.

Table III-2 Mission Adaptive Modes (continued)

MISSION	FUNCTION	WORDS REQ'D	COMPUTATION										CONNECTIVE STRUCTURES		
			TOTAL	RUNNING		INPUT VARIABLE	STORED VARIABLE	DIVISION	MULTIPLICATION	OTHER OPERATORS	COMPARE VALUE WITH LIMIT	COMPARE DIFFERENCE WITH LIMIT	FIX TWO DIMENSIONAL POSITION	INCLUDES: Read input value, make specified comparison and provides output if com- parison is outside limits	
			MEAN	VARIANCE	MEAN										
4. Comet Flyby Con't			23	42	24	59	5	1	3	2	1	14	15	105	
c. Determine time of occultation of the sun by the comet nucleus	Transient	38			24						14				
d. Search RF noise spectrum, stop with signal and track	Transient	39			24							15			
e. Target probe from image information	Guidance	188			48						+20 Compute Component	15	105		
f. Seek maximum coma direction	Feature Extraction	168			48							15	105		
g. Prioritize time, power and data alloca- tions among competing instruments	Controller	1925													
5. Comet Rendezvous															
a. Provide adaptive filtering of spectral lines from coma gas to search for nucleus	Controller	70		42											
b. Detect and track ejecta	Transient	355			96						14 + 14 - to store maximum variance 19 to check for separation & Output	30	210		
c. Navigate to land on nucleus	Navigation	188			48						20 -Compute component velocity	15	105		
d. Determine the impulse required to avoid cometary particles	Controller	52			24		5	2	3	4	14				

Table III-2 Mission Adaptive Modes (continued)

MISSION	FUNCTION	WORDS REQ'D	COMPUTATION										CONNECTIVE STRUCTURES		
			TOTAL		RUNNING		INPUT VARIABLE	STORED VARIABLE	DIVISION	MULTIPLICATION	OTHER OPERATORS	COMPARE VALUE WITH LIMIT	COMPARE DIFFERENCE WITH LIMIT	FIX TWO DIMENSIONAL POSITION	INCLUDES: Read input value, make specified comparison and provides output if com- parison is outside limits
			MEAN	VARIANCE	MEAN	VARIANCE									
6. <u>Cloudy Planet Orbiter</u>			23	42	24	59	5	1	3	2	1	14	15	105	
a. Detect and record Jovian decametric radio bursts	Transient	38			24							14			
b. Provide priority for transmission of repeated images of smaller (and therefore more transient events)	Feature Extraction	214				79						15	to store maximum variance	105	
c. View atmosphere in X-ray and gamma-ray after observing solar disturbances	Transient	38			24							14			
d. Provide correlation of visual or UV spots with IR tracking on dark side	Feature Extraction	540	Estimate												
e. Recognize increase in signal and step up data rate	Transient	38			24							14			
f. Adjust experiment priority by earth command	Controller	10													
7. <u>Atmospheric Probes</u>															
a. Adjust bit rate to accommodate atmospheric absorption	Controller	38			24							14			
b. Transmit pressure-temperature anomalies	Transition	126			96								30		

Table III-2 Mission Adaptive Modes (continued)

Table III-2 Mission Adaptive Modes (continued)														
MISSION	FUNCTION	WORDS REQ'D	COMPUTATION								CONNECTIVE STRUCTURES			
			TOTAL	RUNNING		INPUT VARIABLE	STORED VARIABLE	DIVISION	MULTIPLICATION	OTHER OPERATORS	INCLUDES: Read input value, make specified comparison and provides output if comparison is outside limits			
				MEAN	VARIANCE						MEAN	VARIANCE	COMPARE VALUE WITH LIMIT	COMPARE DIFFERENCE WITH LIMIT
7. Atmospheric Probes Con't			23	42	24	59	5	1	3	2	1	14	15	105
c. Terminate gas chromatograph cycle with no output	Controller	38			24							14		
d. Terminate non-productive instruments	Controller	38			24							14		
e. Signal chemical analysis of atmosphere after sensing electrical activity	Transient	38			24							14		
f. Sense and sample discrete cloud levels by changes in nephelometer or radiometer	Transition	38			24							14		
g. Protect sensitive instruments from exposure to damaging radiation levels	Controller	38			24							14		
8. Mars Lander (in addition to Venus lander)														
a. Disable seismometer high data rate shift when wind is blowing	Controller	38			24							14		
b. Determine cloud height by stereo viewing from rover and lander	Transient	336			96								30	210
c. Search for earthquake lights after signal from seismometer	Transient	38			24							14		

IV. APPLICATION OF ARTIFICIAL INTELLIGENCE TO SPECIFIC MISSIONS

The discussion of adaptability in Chapter III emphasized the positive aspects of the possibilities for using adaptability to improve scientific output. In this chapter a more critical approach is taken.

In Section A the missions are given a preliminary ranking for potential value of adaptability considering only certain mission parameters without regard for the actual adaptive modes that have been identified.

In Section B the various missions are then considered to see which adaptive modes will give substantial advantages that could not be obtained without on-board artificial intelligence (AI). Wherever possible, numerical estimates of improvement are given.

In Section C the missions are ranked according to the benefits to be obtained through the use of on-board AI to obtain adaptability.

A. MISSION PARAMETERS THAT AFFECT ADAPTIVE POTENTIAL

Examination of certain mission parameters gives a clue to the extent that adaptability will increase the scientific yield. In this section these parameters are compared for the selected solar system missions and some preliminary conclusions are drawn.

"Round trip communication time," as used here, is the time required for radio signal propagation from spacecraft to Earth and return. It is an absolute lower limit on the time between stimulus and response if the decision to respond is made on Earth. In the real world, one should add times for communication system lock-up (carrier and sub-carrier phase lock, symbol lock, etc.), data transmission, data decoding and presentation, decision making, command coding, command transmission, and command verification if required. These extra delays can be greatly reduced by improved technology such as data handling and displays and error control for the command system. The propagation time, however, will not be reduced since it is, of course, determined by the speed of light.

Figure IV-1 shows the round trip communication times for the various missions. The spread of times is a result of the changing Earth-planet distance during the lifetime of the mission or for different mission opportunities.

Long communication times make response to transients more difficult when controlled from Earth and make on-board decisions more important.

Another parameter of interest is the number of radio wave round trips that can be made during the active part of a mission. This is called the normalized mission duration and is an upper limit on the number of serial trial-and-error adjustments that can be made.

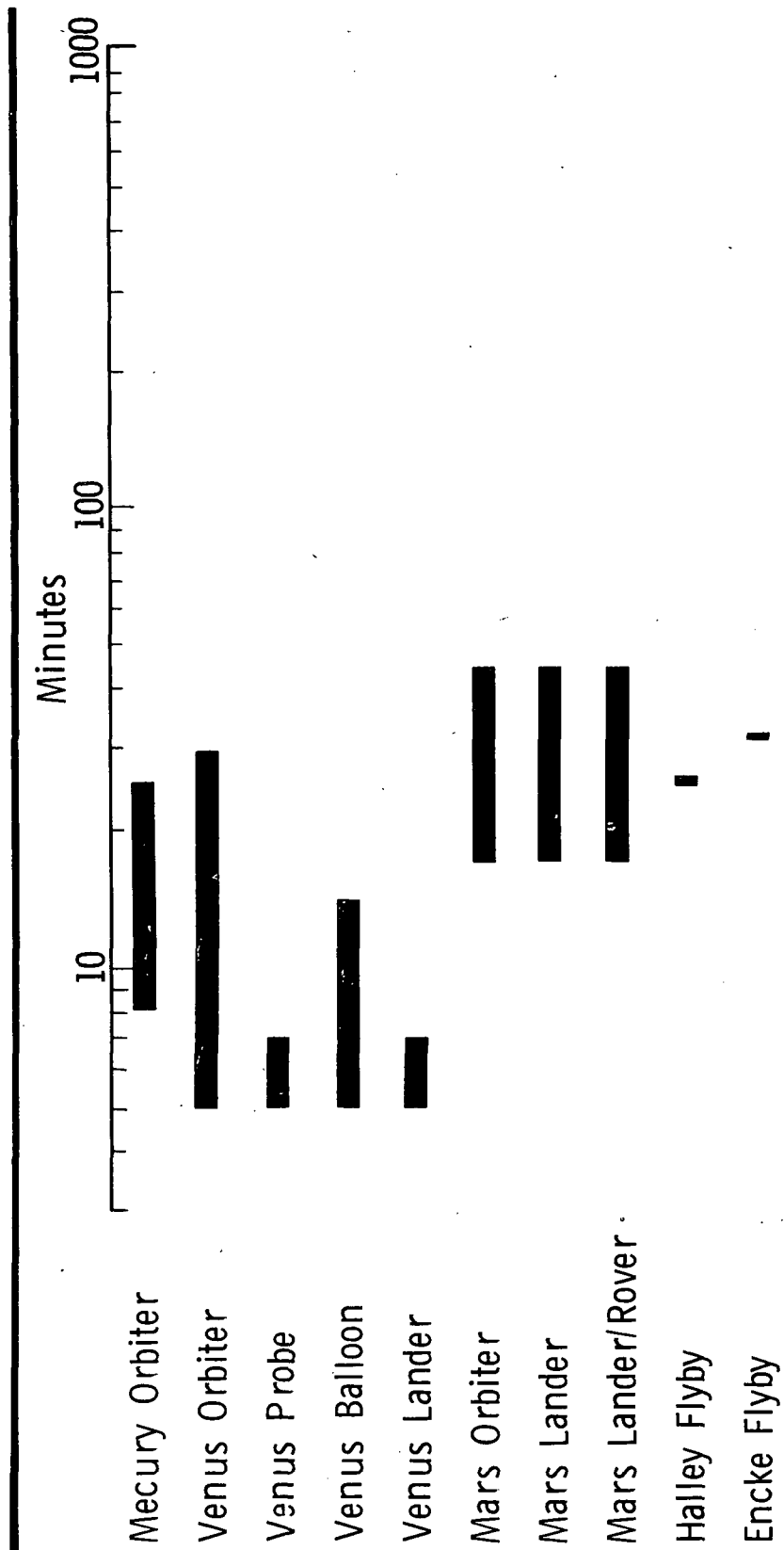


Figure IV-1 Round Trip Communication Times

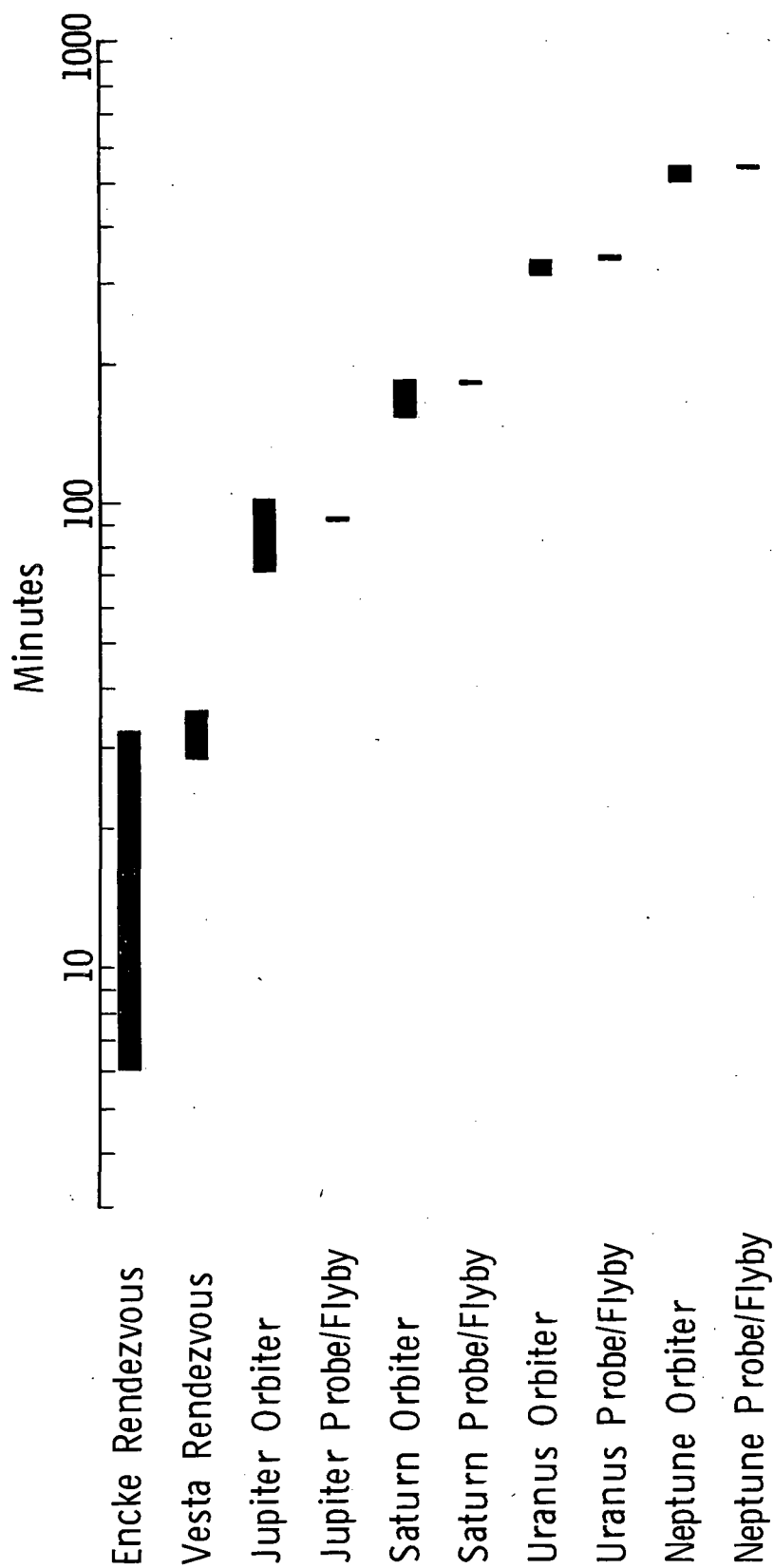


Figure IV-1 Round Trip Communication Times (concluded)

From Figure I-2 it is evident that the outer planet probes must operate without help from Earth and any adaptations must be made on the probes or possibly on their flyby vehicles.

Although large normalized mission durations make Earth-based control easier, they also make adaptive systems with on-board decision making more practical. The ability to revise an adaptive system on the basis of experience is extremely valuable, because it makes it possible to check it out gradually, giving it more autonomy as confidence is gained. Criteria and thresholds can also be tuned to optimize performance under the actual conditions. If there is no opportunity to adjust the system, it must be designed to operate in a very wide range of environmental conditions.

Available data rates for the missions are shown in Figure IV-2. The ranges are related to distance from Earth.

The use of the higher rates requires significant modification and upgrading of the DSN ground stations, and in some cases, the Earth-based communications between ground stations.

Total available data volumes are shown in Figure IV-3. Data volumes for orbiters are estimated by multiplying the peak available data rate by 20% of orbit time for a nominal 400 Earth day mission. The data volume for flybys is based on the time required for traverse in and out of distance equivalent to 100 planet radii. Mission time for an outer planet probe is taken from current studies. The lifetime of the Venus lander is set at 1.5 hours. For the comet flybys, storage capacity was assumed to be 3×10^{10} bits, comparable to the Earth Resources Technology Satellite (ERTS) recorder. The Venus balloon lifetime was set at 60 days.

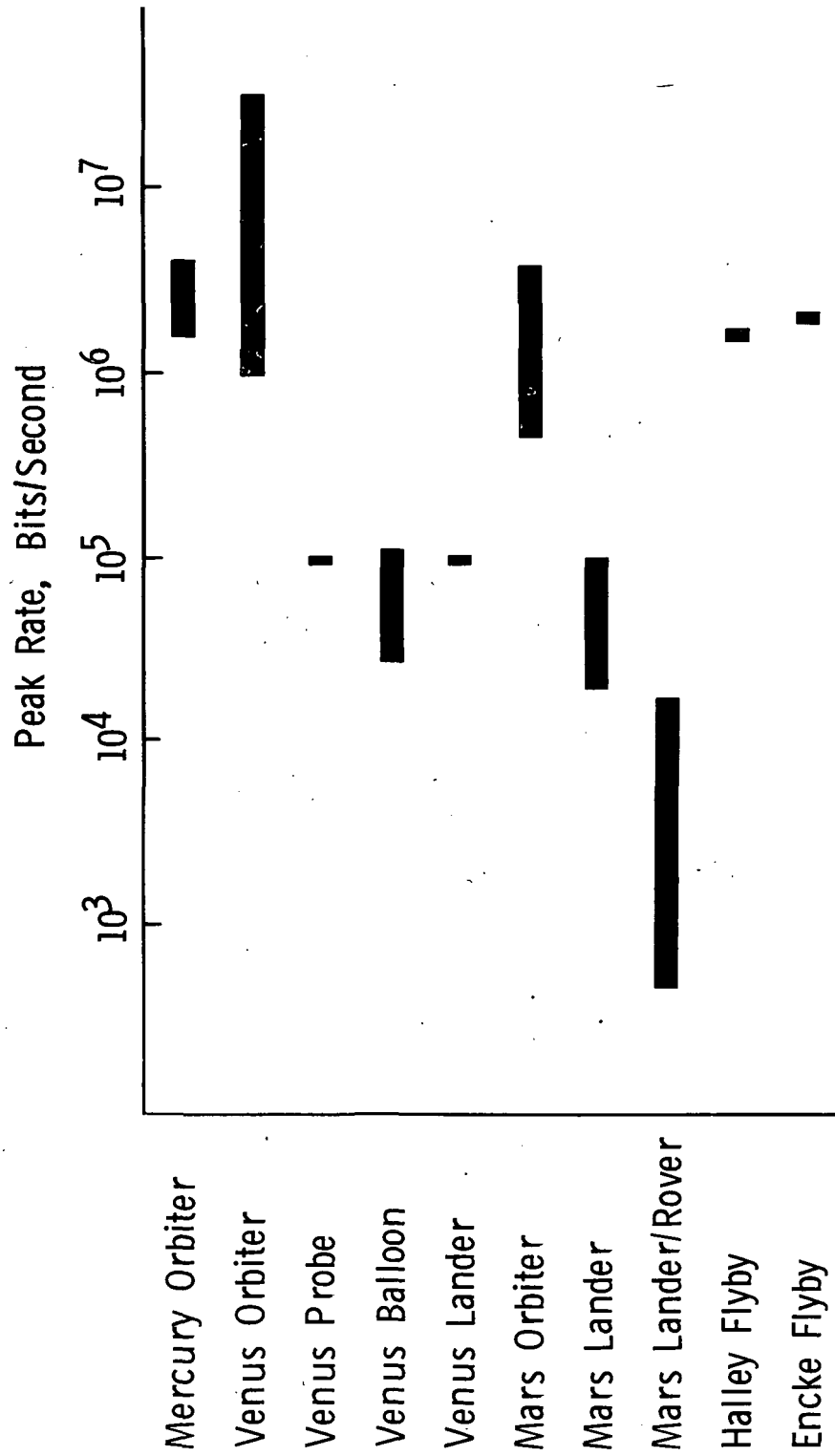


Figure IV-2 Available Data Rate

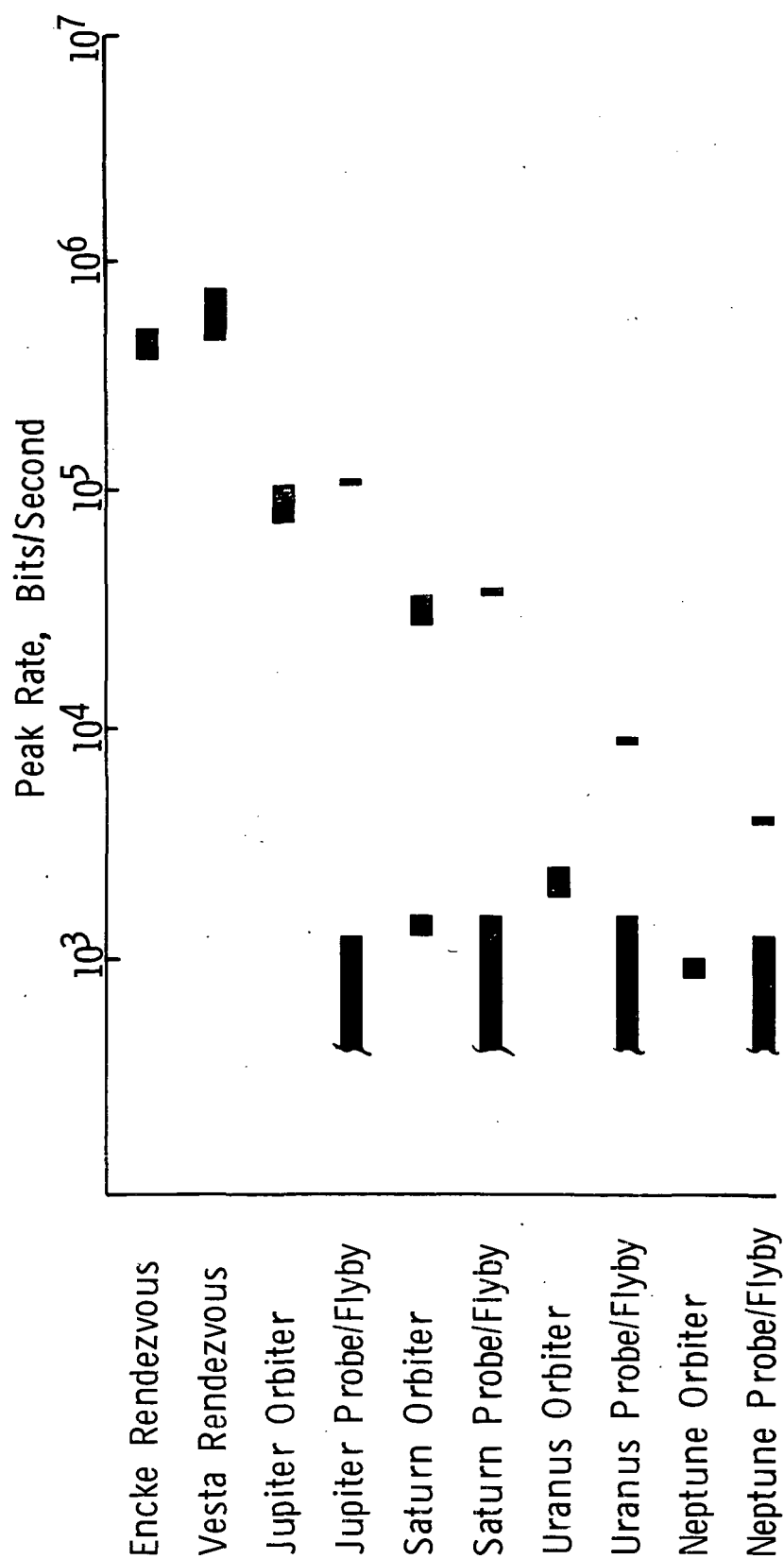


Figure IV-2 Available Data Rate (concluded)

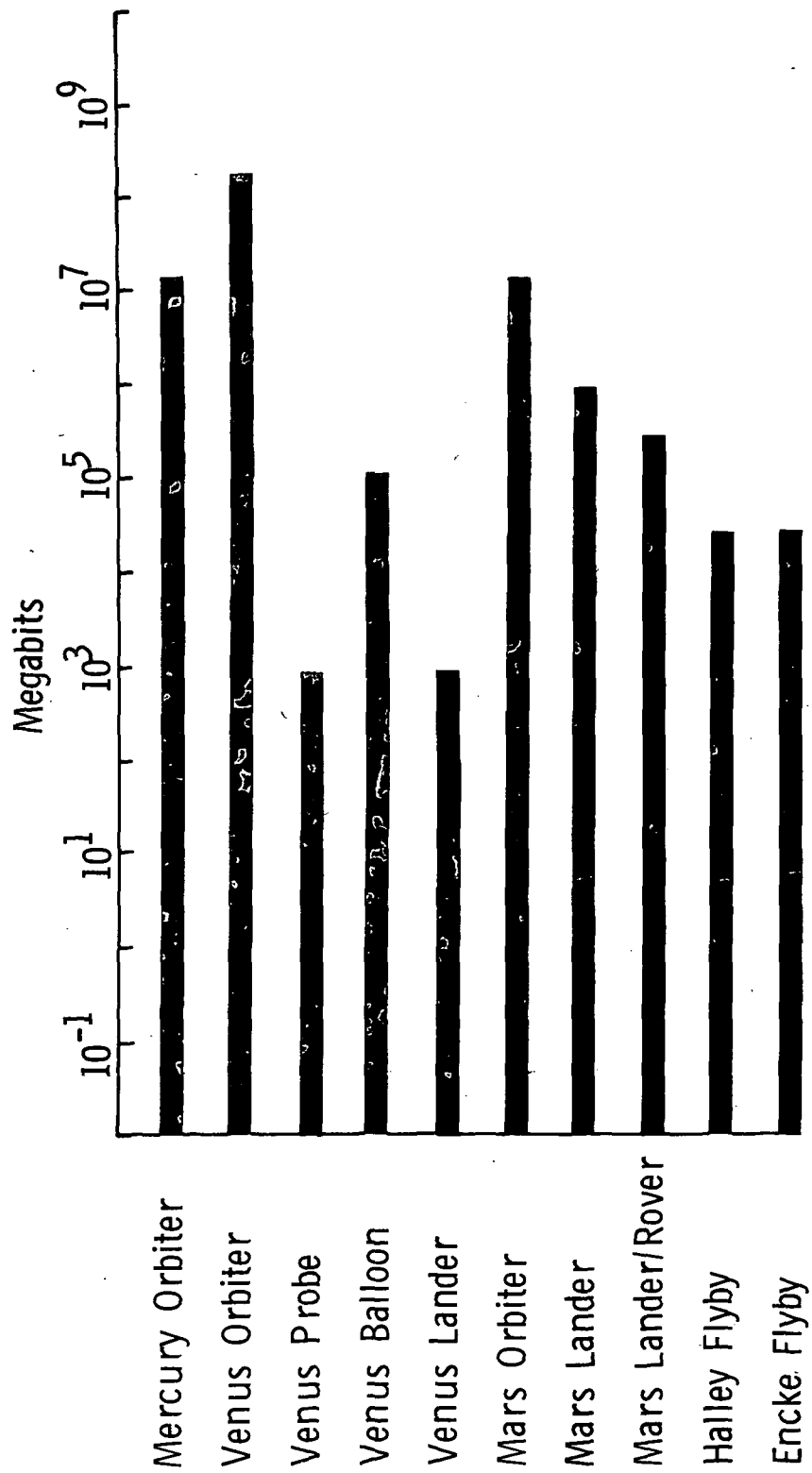


Figure IV-3 Total Available Data

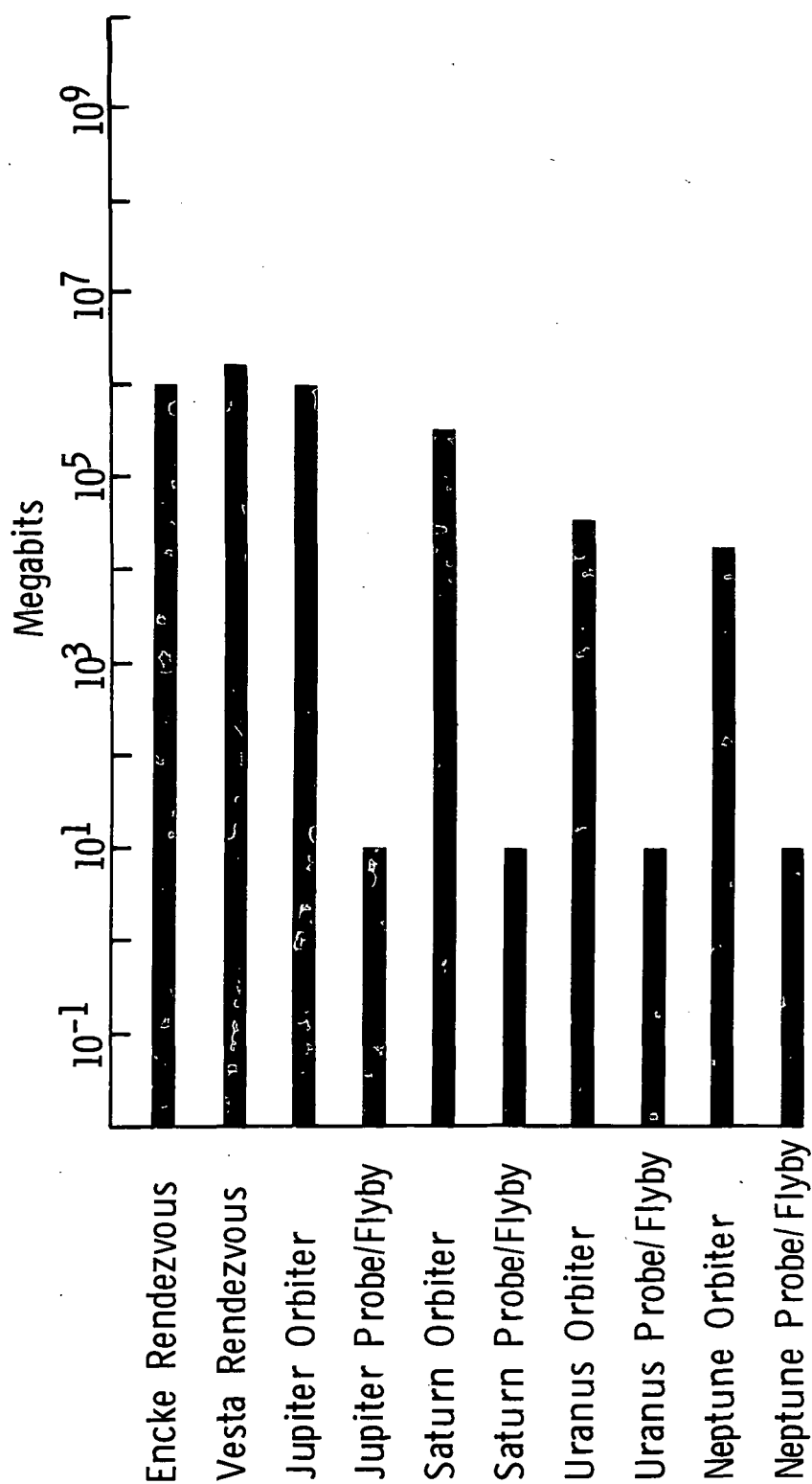


Figure IV-3 Total Available Data (concluded)

These figures indicate that data transmission may not be a serious bottleneck for the post-Viking missions. If the numbers seem optimistic, one can recall that Mariner 4 transmitted about 8 bits/second compared to several thousand bits/second for Mariner 9.

The weight available for science instrumentation for each of the planetary missions studied was shown in Figure II-7. The science weights are consistent with the power and data capability available on board the orbiting or flyby vehicles.

The weight available for science on board the planetary probes, balloons and landers was determined by scaling up specific probes, balloons and landers that were previously studied at MMC under contract to JPL, NASA/Goddard and NASA/LRC.

A large science payload generally indicates a rich complement of instruments and greater possibilities for adaptability.

Table IV-1 shows a ranking of solar system missions for the applicability of adaptive features based only on the communication parameters and available weight for science.

Table IV-1 Ranking for Adaptability by Mission Parameters

Outer Planet Probes
Venus Probe, Venus Lander
Halley Flyby, Encke Flyby
Neptune, Uranus, and Saturn Orbiters
Venus Balloon
Mars Lander/Rover
Mars Lander
Jupiter Orbiter, Vesta and Encke Rendezvous
Mars, Mercury, and Venus Orbiters

For the missions at the top of the list it is impossible to provide any control from Earth because the active mission times are less than the round trip communication times. The missions at the bottom of the list can return very large volumes of data and there is no great incentive to use on-board decision making to select data items to be transmitted.

B. EVALUATION OF BENEFITS

Table III-2 from the previous chapter will be followed in making a critical assessment of the adaptive modes that have been listed, and the heading numbers and letters used below correspond to those in the table.

1. Mercury Orbiter and Asteroid Rendezvous

a. TV Exposure Adjustment - The idea here is to make sure that any extremely dark features are given enough exposure to reveal details. A dark feature is first identified in one picture and then a special exposure is made on a subsequent orbit. The value of this mode depends on the dynamic range of the imaging system and the characteristics of the planetary surface. On Mars, the problem has been getting enough contrast rather than coping with extremes, but some very dark features have been found on the Moon and may be found on Mercury and the asteroids. On the other hand, electronic imaging systems can be made with very large dynamic ranges. Furthermore, if the data processing and delivery system is fast enough, it will be possible to command the special exposures from Earth. Unless further study indicates a real need for this mode, it is probably of marginal value.

b. Anticipation of Solar Flare Effects - Solar flares can give increases of several orders of magnitude in the x-ray flux. During the flares, the x-ray fluorescence spectrometer can be operated with greatly improved resolution to give more detailed mapping of the elemental composition of the surface. Control from Earth would be too slow to get much advantage from any but the largest flares. This adaptive mode would yield information that could not otherwise be obtained.

The expected number and intensity of flares, and thus the expected benefit of this mode, depend on the phase of the solar activity cycle when the observations are being made.

c. Track Terminator to Look for Outgassing, Albedo Changes, or Atmospheric Changes - The following remarks also apply to e. below. The total available data capability of the nominal Mercury orbiter mission is 10 million megabits, sufficient for about 2 million pictures. In the early stages of the mission, enough pictures could be taken of the limb and terminator to determine whether transients are actually present. If so, more camera time could be allocated to watching for them. Therefore, it does not appear to be necessary to use onboard AI to capture the transients. However, examination of millions of pictures is a task that should use some computer help, and the tradeoff may be in the partitioning of AI between the spacecraft and the data centers on Earth.

d. Asteroid Landing Site Selection - The low escape velocities for the asteroids, 100 to 170 meters/second for Vesta, make it easy to control the landing to take advantage of data gathered during the descent. The general area for landing would be chosen by the scientific team with the help of pictures taken from altitudes of a few tens of kilometers. The on-board AI can use the

imaging data for terminal guidance to the selected spot and also to avoid slope and rock hazards. The low gravity and lack of weathering make the probability of dangerous slopes very high.

Because of the low surface gravity, it may be feasible to recover from an upset by using the propulsion system.

e. Track Limb to Look for Clouds - See c. above.

f. Direct the TV Toward Thermal Anomalies - The remarks under b. above apply here also. Good image coverage will not be difficult, and it is probably feasible to make decisions for special pictures from the Earth.

2. Venus Balloon

a. Search for Surface Anomaly and Start Detailed Radar Mapping or Drop a Probe - Round trip radio times from Venus are short, about 5 to 15 minutes, and it may be feasible to make the decisions on the Earth. On the other hand, on-board control would be very simple if it only involves triggering the action when the radar altimeter and barometric altimeter differ by some specified amount indicating a certain ground elevation. Another simple criterion would be to put a threshold on the change in elevation within a specified time.

A combination of Earth-based and autonomous control appears likely. Targets could be selected in advance on the basis of data gathered by Earth-based radar before the mission. As a target is approached, the science team can set up the autonomous system to trigger at the optimum point.

b. Control of Inflation Gas Generation - The evaluation of the benefits of this mode requires a study of balloon dynamics under the conditions anticipated in the atmosphere of Venus. After suitable control equations have been devised it will not require much computer capacity to implement them.

c. Raise Tethered Probe When Atmosphere is Turbulent - Benefits of this mode depend on unknowns such as the frequency of damaging storms and whether a probe could be retrieved in time to avoid damage. The computation cost would be small, but the mechanism and power for raising the probe might be considerable.

d. Stop Transmission at Earth-set - The following remarks also apply to e. below. These modes are extremely simple to implement. Earth-set would be detected by a weakening of the signal from Earth or by its absence during a scheduled transmission period. To avoid premature triggering when trouble on Earth cancels a transmission, the Earth-set detector can be armed a short time before the balloon is expected to pass over the horizon.

e. Turn on Night Instruments at Sun-set - See d. above.

f. Transmit TV Only When Detail is Present - Our assumptions on the communication system for the balloon give 10^5 megabits as the total information that can be returned for the entire mission. This large number does not permit as much coverage as one might expect. For instance, if we assume a pixel spacing of 10^{-4} radian (0.3 minute of arc), it takes 6.3×10^8 pixels to cover a hemisphere. With 40% overlap, 3 colors, and 5 bits per pixel for each color, a complete hemispheric mosaic could only be transmitted about 7 times during the mission.

For a balloon that is mostly in or slightly above the clouds, the yield of interesting pictures could be tremendously increased with some adaptive direction of the picture taking. Control should be divided among 3 modes: a scheduled sequence, on-board selection based on contrast and other characteristics, and a direct command over-ride of the other modes. The scheduled sequence would provide a systematic coverage of all angles to permit the science team to see what was being passed over by the on-board selection. It would also give them the information they need to improve on the on-board selection criteria as well as to issue direct commands. As the mission progresses, the scheduled sequence would probably be used less and less with increased emphasis first on the direct commands and then on the on-board selection.

g. Perform Life Detection Experiment When Pre-established Temperature, Pressure, and Composition Conditions Are Met - It is unlikely that a scientist would entrust this important decision entirely to an automaton. If the atmosphere fluctuates too quickly for him to respond from Earth, he might want to set up the automatic control to trigger the sampling mechanism the next time certain conditions are met. As with many of the adaptive modes, it is important here to develop automatic features that will increase the scientist's control and help him get the results he wants.

h. Detect Atmospheric Anomalies to Signal Data Rate Increase - The available data rate is so much larger than required for reporting atmospheric changes that the savings would not be important. It might still be worthwhile to relieve the science team of the necessity of reviewing large volumes of uninteresting data. The selection could, however, be done after receipt of the data on Earth.

3. Venus Lander

a. Cut Off Non-productive Instruments - This mode reduces power consumption and delays death by overheating. Its value will depend in part on the value of additional time on the surface. A longer time will give a better sample of seismic activity. It may also permit pictures to be taken after settling of a dust cloud stirred up by the landing.

b. Determine Direction of Maximum and Minimum Contrast for Optimum TV Coverage - The following remarks also apply to d. below. If the lander is sure to be able to make a full panoramic picture of its surroundings, it will not be necessary to be selective, and the value of this mode will be small. A picture 30 degrees high and 360 degrees wide with 0.7 milliradian pixel spacing (as with the Viking lander) will have 6.4×10^7 pixels. With 3 colors and 6-bit quantization (64 levels) a total of 1.15×10^8 bits must be transmitted. The assumptions made in Section II. C led to a communication link capability of 10^5 bits/second, and thus about 20 minutes to transmit the full panorama. With these numbers, selective picture taking is not necessary if the life of the lander is at least a little longer than 20 minutes and the imaging system is the only large source of data. However, actual missions may be designed with much less communication capability, better image resolution, or more than 3 spectral (color) bands, and adaptability may make the difference between full coverage of the interesting areas and partial coverage, most of which could be wasted because of poor visibility.

c. Switch Attention to Seismic Event - The value of this mode also depends on the communication capability. Seismic bandwidths are typically low, usually much less than 100 Hz. With 200 samples/second, 10-bit quantization, and 3 axes, the data

rate will be 6000 bits/second. This could exceed the capability of an austere lander but would be a small load for the 10^5 bit/second rate assumed for the baseline.

d. Limit Upward Sweep of TV Scan When Detail Ends - See b. above.

e. Detect Changes in Atmospheric Wind, Dust, Temperature, and Composition to Signal Emphasis Change - The meteorological instruments put out even less data than the seismometers, and the gains from this particular adaptive mode are likely to be small.

f. Detect Changes in Illumination and Determine Cause with TV Scan - Since we know so little about conditions on the surface of Venus, the value of this mode is completely speculative.

g. Detect Chemical and Physical Differentiation in Immediate Vicinity of Lander; Signal Dispatch of Rover or Reach Out - Sensors for this mode would be an x-ray fluorescence spectrometer or a multispectral sensor in the visible and IR. They could be attached to a sample-collecting arm or a rover. Because of the short mission lifetime, non-adaptive random gathering of samples would probably yield only a single soil or rock type. With the adaptive system, a rapid search could be made and several different types could be collected for full analysis, assuming that different types are in fact within reach.

h. Detect Electric or Sonic Disturbances - Like f. above, this mode is impossible to evaluate without better knowledge of conditions at the surface.

4. Comet Flyby

a. Provide Image Motion Compensation - If image motion is compensated without an adaptive system, the relative motion of the probe and the comet must be accurately predicted. Use of an image motion sensor to control the compensation could save cost by relaxing requirements on the accuracy with which the probe must be tracked from Earth, and it could also make a closer approach practical.

b. Provide Adaptive Filtering of Spectral Lines from Coma Gas to Search for Nucleus - The gas composition can probably be determined a few days before encounter, and it should be possible to decide on Earth which filters should be used. On-board AI appears unnecessary for this mode.

c. Determine Time of Occultation of the Sun by the Comet's Nucleus - The time of occultation must be determined to about 1 second to get a picture of the nucleus silhouetted against the Sun. Prediction to this accuracy is very difficult mostly because of the uncertainty in the comet's ephemeris. On-board sensing of the darkening of the Sun is easy. This adaptive mode will greatly increase the chance of getting a good silhouette with only a small cost in on-board complexity.

d. Search RF Noise Spectrum, Stop with Signal and Track - Because of the short time spent close to the comet, it is unlikely that good data on the time variation of radio noise can be obtained without the scan-and-track mode.

e. Target Probe from Image Information - Making the decision on board would save about 1 hour in round trip propagation time and the time required to transmit a picture. This assumes that little time is lost in getting the data to the person or computer

on Earth that will calculate the corrections to the nominal release time and propulsion schedule of the probe. Using on-board decision making may save cost by relaxing the angular accuracy that is needed for the attitude reference and imaging systems because the spacecraft will be nearer to the comet when the last and critical picture is taken.

f. Seek Maximum Coma Direction - It might be desirable to perturb the trajectory of the spacecraft to make it pass on the side where the coma is most (or least) dense, assuming that some irregularity in the surface makes the coma unpredictably asymmetrical. The advantage is speculative and if trajectory is adjusted, it will have to be done long before encounter so that the advantage of an on-board decision is small.

g. Prioritize Time, Power, and Data Allocation Among Competing Instruments - The utility of a priority system will depend largely on whether a good set of criteria can be written before the mission. Unlike missions of longer duration such as the planetary orbiters and the Mars landers, the comet flyby missions have such a brief active period that it will be difficult at best to modify the priority rules. If a bad choice of rules is made, the results can be worse than would have been obtained with a fixed sequence of activities. After the data from a first comet flyby have been digested, it may be possible to increase the yield of the second one with a simple on-board controller that decides priorities on the basis of the data coming in.

5. Comet Rendezvous

a. Provide Adaptive Filtering of Spectral Lines from Coma Gas to Search for Nucleus - This function can be provided with control from Earth and does not require on-board decisions.

b. Detect and Track Ejecta - This is an ideal opportunity for on-board AI. If ejecta are to be observed in detail they must be detected promptly, and decision making on Earth will be too late. On the other hand, there will be adequate time during the mission to check the operation of the imaging system and the computer routine that locates the main body of the comet and will also detect pieces that are thrown off. Brightness thresholds and other criteria can be tuned up to get good sensitivity to cometary particles while discriminating against stars.

c. Navigate to Land on Nucleus, and

d. Determine the Impulse Required to Avoid Cometary Particles - These two modes are considered together because the danger from particles will be greatest as the comet is approached, and the navigation problem is not difficult to control from Earth unless the spacecraft must dodge particles. The particle avoidance technique can be adjusted from Earth before the spacecraft ventures into the region of danger. The value of these modes will depend on whether there are enough particles being ejected or orbiting to be dangerous, and this can probably be determined from an earlier flyby.

6. Cloudy Planet Orbiter

a. Detect and Record Jovian Decametric Radio Bursts - This mode will permit detailed wide-band recording of bursts without overloading the data system with uninteresting background noise. The signal threshold for starting to record and the frequency coverage can be adjusted from Earth during the mission to take advantage of experience. Thus there is no risk of losing all the data because of setting the threshold too high.

b. Provide Priority for Transmission of Repeated Images of Smaller and Therefore More Transient Events - Although regions with small details are likely to be rapidly variable, the selection of features to be imaged repeatedly at short time intervals can be controlled by the science team and will be revised during the mission as more is learned of the nature of the atmosphere.

Figure IV-4 shows the geometry and time relations near periapsis for a typical Jupiter orbiter. A particular point on the surface can be observed for about 4 hours, giving a good opportunity for observing features of atmospheric circulation such as convection cells, zonal shear, and spot motion.

To get good recording of motions, pictures should be made at intervals not less than the time it takes an active object to move 10 pixel intervals. With an angular pixel spacing of 10^{-5} radian and periapsis radius equal to 5 radii of Jupiter, the spacing on the surface will be less than 3 km for almost 8 hours near periapsis. With a nominal wind speed of 0.1 km/sec, a cloud would move 1 pixel spacing in half a minute. It is obviously impossible to cover the planetary disk with pictures taken this rapidly. For instance, if the available data storage is 3×10^4 megabits, it is possible to record 4,300 pictures each

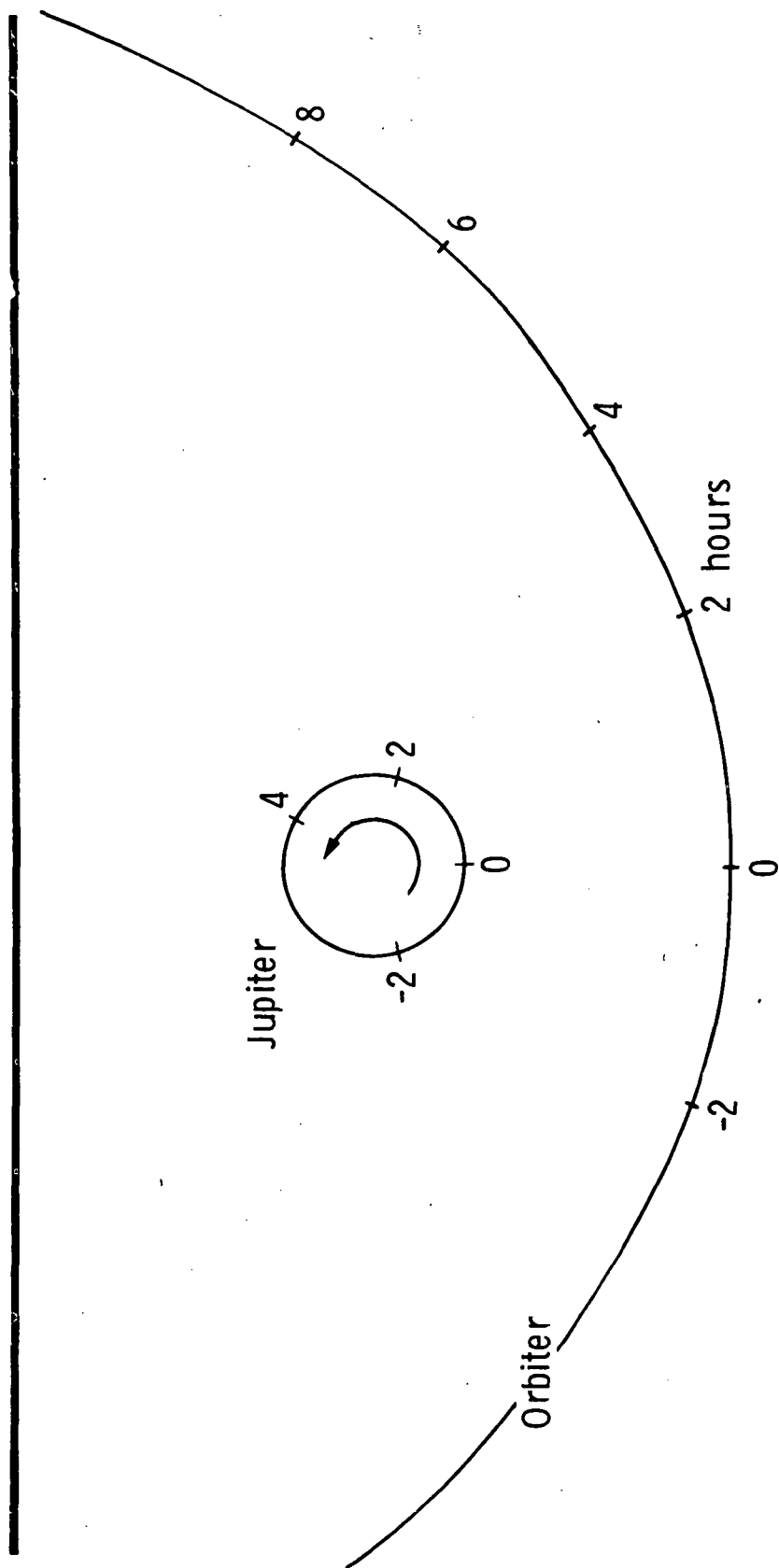


Figure IV-4 Jupiter Orbiter Periapsis

containing 1000 x 1000 pixels quantized to 7 bits (128 levels). A non-adaptive system could cover 50% of the disk in 3 colors with 40% overlap. If some of the capacity is used to make repeated exposures of selected regions, there is no assurance that these regions contain enough detail to show motion.

With an adaptive system the general coverage might be reduced to 38% and the remaining capacity used for movies (40 frames each) of 25 locations selected for fine detail or other special features.

For Saturn, Uranus, and Neptune orbiters, adaptability is even more important because of the smaller amounts of data that can be returned.

c. View Atmosphere in X-ray and Gamma-ray After Observing Solar Disturbances - Observing the interaction of a solar flare with the atmosphere of a planet is an opportunity not to be missed. Rapid response is essential and therefore Earth-based control is not satisfactory. This mode will yield data that would not otherwise be obtained.

7. Atmospheric Probes

a. Adjust Bit Rate to Accommodate Atmospheric Absorption - This mode is more valuable if there is a 2-way communication link between the probe and the flyby spacecraft. In this case the error rate can be monitored and the bit rate adjusted to take advantage of all variations that affect fidelity including equipment performance. Although it might be possible to get improvements of a factor of 2 or more in returned data, the return link may not be justifiable unless it is also used for 2-way doppler measurements or to reduce the electronics in the probe by making use of the spacecraft's computer.

b. Transmit Pressure-Temperature Anomalies - Pressure and temperature vary smoothly with time from entry, and it may be possible to reduce the number of data points by a large factor without decreasing the amount of useful information. The utility of this mode depends on a tradeoff between hardware required for adaptability and the saving in the communication hardware. If the probe has a computer, the hardware cost is negligible, but a probe with a computer will probably carry much more prolific sources of data than the temperature and pressure probes, and the reduction in total data rate may not be significant.

c. Terminate Gas Chromatograph Cycle When Output Stops - On the assumption that the time spent in the chromatograph column is proportional to the square root of the molecular weight, if the run is stopped after it has been found that weights 40 through 50 are absent instead of waiting long enough for weight 100 to emerge, the time required is reduced by a factor of the square root of 2, and 40% more runs can be made. Of course if the heavier weights are present in the atmosphere, nothing is lost or gained.

d. Terminate Non-Productive Instruments - The remarks under 3. a. apply here.

e. Signal Chemical Analysis of Atmosphere After Sensing Electrical Activity - If samples are to be taken at regular intervals, it will be easy to modify the sequencing system to take an extra sample (or take a regular sample earlier than scheduled) when lightning or something similar is detected. If an adaptive controller is available on the probe, this mode should be included although with present knowledge it is hard to estimate its value.

f. Sense and Sample Discrete Cloud Levels as Detected by Changes in Nephelometer or Radiometer Outputs - There is good theoretical reason to believe that the individual cloud levels are homogeneous, and planetologists believe they know about how many to expect. The operation of this mode can therefore be well planned and has a high chance of success.

8. Mars Lander

a. Disable Seismometer High Data Rate When Wind is Blowing - This mode is very easy to implement if the on-board computer has access to the anemometer output (which it will not in Viking). It is certainly cheaper than deploying the seismometer and still gives some equivalent benefits.

b. Determine Cloud Height (and distance) by Stereo Viewing from Rover and Lander - When clouds are detected it is important to know their distance at least approximately. Combined with a sequence of pictures at intervals of a minute or so, a knowledge of the range makes it possible to determine wind speed from the motion of cloud elements. It will also show whether the clouds are associated with particular mountains.

The separation between the Viking lander fax cameras is inadequate for ranging beyond about 100 meters. However, a rover camera can be used with a lander camera to get useful range information.

The range error E is given approximately by the relation

$$E = R^2 P / B \sin A$$

where R is the range, P is the parallax uncertainty, B is the stereo baseline, and A is the angle between the baseline and the line of sight. P is approximately equal to the angular pixel spacing, 7×10^{-4} for the Viking fax camera.

With the Viking lander cameras alone looking perpendicular to their baseline of about 0.7 meter, the range of an object at only 100 meters distance will have errors up to 10 meters, or 10%. This is obviously inadequate for cloud ranging.

With the small rover, the baseline can be as large as 100 meters, and 10% accuracy can be obtained to 14 km range, and with $B = 1$ km, possible with the medium rover, the range is extended to 140 km.

If there is a common landmark whose range is known in both pictures it can be used as a reference. Otherwise the parallax can be measured by having each camera make a picture of the other. The angles between the baseline and the two lines of sight are determined from the camera azimuth and altitude angles.

Correlation of the pictures can be done on the Earth since the range information is not needed for making decisions on Mars.

c. Search for Earthquake Lights After Signal from Seismometer - The probability of success would certainly be small with such an experiment on Earth, and unless there is a good reason to expect many more violent earthquakes on Mars than on Earth, it is difficult to argue in favor of this mode.

d. Search for Auroral Discharge Using Magnetic Field Change as Signal - This mode can easily be programmed into the executive controller and can use a modified cloud search routine either triggered by magnetic changes or on a more or less regular nightly schedule. It is not even necessary to plan this mode in advance, since it could easily be set up after landing by making simple changes in the priority equations, angular range, and dwell time of the cloud search routine.

This mode ranks high for potential value and low cost.

e. Expose Fax Camera for Constant Integrated Signal Per Pixel - This mode could reduce camera time by a factor of 2 or more. However, the bind is more likely to be in data storage or transmission capability than in camera time. Variable scan speed will not only complicate the data system but will also require modifications to the scan motor drives.

The benefit-to-cost ratio of this mode appears low.

f. Landing Site Selector - If landing site selection increases the probability of mission success by even 10%, it is worth 10% of the mission cost. By reducing the probability of a catastrophic landing it also permits a wider choice of regions to land in.

g. Sample Screening and

h. Rover Control - Sample screening has greater value when a rover is used to gather samples since many more samples can be picked up than can be carried back to the lander and analyzed in detail. As an estimate of the value of an autonomous system with sample screening and simple hazard avoidance, consider the following example.

Assume that the common rocks around the lander have been collected and analyzed. The objective is now to gather six rare rocks, "rare" meaning that they constitute 1% of the available samples. Other assumptions are:

- 12 hours per day link with Earth through Lander (equatorial landing)
- 24 minute average round trip communications delay time
- average traverse segment is 10 m between updates in Earth-directed mode
- average distance between samples is 5 m
- neither mode is penalized for decision-making times

- . three sampler command sequence updates are required to acquire a sample in the Earth-directed mode
- . the autonomous system operates continuously
- . "screening" involves XRFS analysis and storage/rejection decision.

Table IV-2 shows how the times for autonomous and Earth-directed systems can be compared. Depending on how the influence of the assumptions is interpreted, the 20/1 time advantage shown for the autonomous system can be called either optimistic or pessimistic. However, it is clear that autonomy will provide large gains.

i. Control Drill or Other Sample Gatherer - If the drill is mounted on the lander and only one hole is made, slow drilling with Earth control is adequate. When the drill is on a rover, a day or more of rover time may be saved for each hole drilled.

j. Lightning Detector - Thunder Detector - See 7. e.

k. Automatic Focusing of Microscope - The curve in Figure IV-5 is for a family of microscopes with apertures chosen to minimize the combined effects of diffraction and focal error. With automatic focusing, the limit of resolution is in the neighborhood of a wavelength of light, about 0.5 micrometer (0.0005 millimeter). The focal error of non-adaptive systems depends on the nature of the object to be observed and the mechanism for placing the object in front of the microscope (or for positioning the microscope over the object). Practical limits for unprepared specimens probably fall between 500 micrometers and 2000 micrometers. Without automatic focusing, therefore, the entire range of resolution from 0.5 micrometer up to 20 or 40 micrometers is unobtainable.

Table IV-2 Collecting Six Rare Rocks

Sortie Objective: Find Six Rare (One in One Hundred) Rocks

<u>Requirements</u>		<u>Earth Directed</u>		<u>Autonomous</u>	
		<u>Rate</u>	<u>Time(hr)</u>	<u>Rate</u>	<u>Time (hr)</u>
Mobility	3 km	0.01 km/hr	300	0.25 km/hr	12
Sample Acquisition	600 samples	2.4 hr/sample	1440	0.1 hr/sample	60
Sample Screening	600 screenings	0.8 hr/screening	480	0.05 hr/screening	30
Total Times →			2220		102

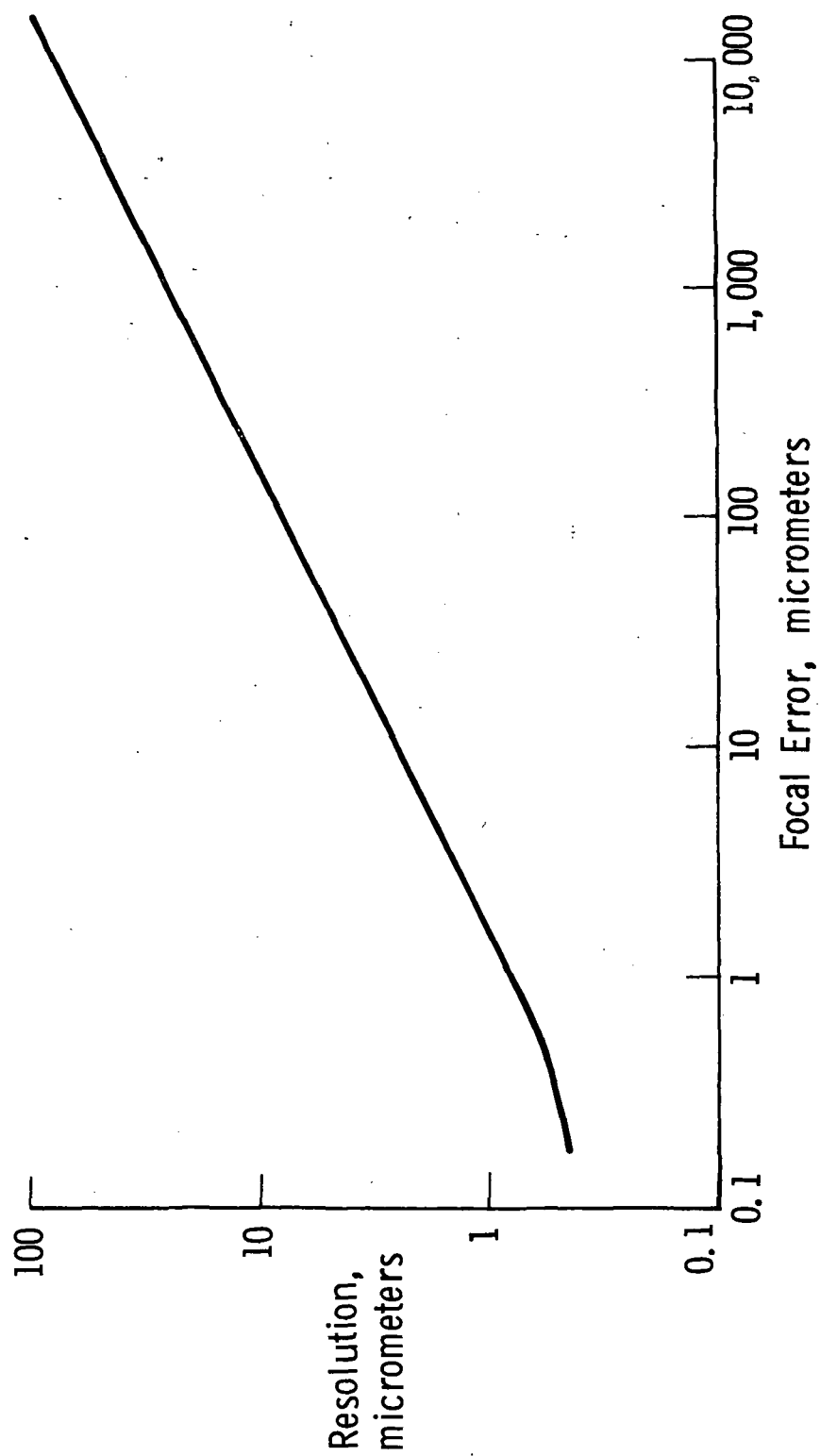


Figure IV-5 Performance of Diffraction Limited Microscopes vs Focal Error

Adjusting the focus by control from Earth is not practical because of the large round trip communication time and the many steps required to get a good focus.

A microscope with automatic focusing is described in Appendix B.

9. Cruise

a. Detect RF Signal from Solar Flare and

b. Couple All Particle and Field Instruments to Boost Data Rates for All When One Detects a Transient - If the spacecraft needs an adaptive system for another phase of its mission, such as orbiting or landing on a planet, it will be simple to include these modes. The total data volume can be greatly reduced with better coverage of interesting events. Cost savings may be realized in reduced operating time for ground stations.

C. RANKING OF MISSIONS FOR VALUE OF ADAPTABILITY

Table IV-3 is a ranking of missions in decreasing order of the value and applicability of on-board AI for adaptability. The ranking is based on the items discussed in Section B of this chapter.

Table IV-3 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

The Mars lander with rover ranks highest because of the very large number of decisions that must be made to operate the rover and its instrumentation. Making the decisions on Earth would tremendously decrease the terrain covered and the number of samples processed.

The outer planet probes are limited in available data rate and volume, and their active mission times are so short that no decisions can be made on Earth.

The Venus lander can transmit a fairly large volume of data if it lives for the nominal time. However, it is a high risk

mission, and it is important to transmit some good data early in case of premature failure. Devices for examining the soil, such as microscope and drill, must operate autonomously.

The Venus probe and the 2 comet flyby missions must also operate autonomously, but adaptability is less important to success.

The outer planet orbiters have lifetimes large compared to the communication time, but the times in each orbit when they are close to their planets are rather short. Autonomous decisions can help them get good coverage of atmospheric action during these brief encounters. The Jupiter orbiter can get much more data back than can the Neptune orbiter, and therefore the latter will rank higher in need for adaptability.

The remaining missions have long lives, high data rates, and few important decisions to make.

V. NEW TECHNOLOGY REQUIREMENTS

This chapter lists some technology items that need development and would be useful for at least one, but usually several, adaptive solar system missions. The first two items have potential for civil applications in addition.

Pattern Recognition and Feature Extraction Algorithms. A good set of algorithms to use with imaging systems would not only be useful for most of the anticipated space missions, but would also find application in Earth-orbital missions and on the ground. The imaging systems would include those using x-rays (medical diagnosis), visible, IR, and radar (collision avoidance) signals.

Redundant Spacecraft Systems. With the greater boost capability provided by shuttle, it will be much cheaper to get reliability with redundant equipment than by designing, building and testing ultra-reliable components. Good techniques are needed for detecting malfunctions and switching in the back-up gear. The problem is complicated by the need to provide redundancy for the detection and switching systems as well. The civil spin-out for this technology is potentially large, mass transportation being one industry that needs very high reliability if it is to be automated.

Multipurpose Spacecraft Computer. This should be a single computer design that can perform all the data handling, logic, and control functions for many different missions. Great cost savings would be realized in not having to design and qualify as much hardware for each mission. If a fairly versatile and fast processor is at the center of this computer, it can be tailored to different mission requirements by varying the amount of memory. Missions with extremely high speed requirements could possibly be accommodated with multiple processors.

APPENDIX A

SURVEY OF THE PLANETARY MISSIONS

I. ASTEROID RENDEZVOUS

As a group, the asteroids or minor planets occupy orbits around the Sun which are generally between those of Mars (1.5 AU) and Jupiter (5.2 AU) although some of them can penetrate much more into the central regions of the solar system and can at times come quite close to the Earth. The inclinations of their orbits to the plane of the ecliptic are generally greater than those of the larger members of the solar system, often of the order of 10° , and sometimes considerably more ([1], p. 120). Likewise, the eccentricities of their orbits are generally much greater than those of the larger planets, with the exceptions of Mercury and Pluto.

Their total number is certainly very large. About 2000 have been identified so far, and their orbits have been determined with an adequate accuracy to find them again. But it has been estimated that there are probably 80,000 or more of them with diameters of 1 km or more, and an undeterminable number of smaller ones.

Their total mass is, however, likely to be very small by planetary standards. The order of 0.1 Earth mass has been estimated for their combined mass from secular perturbations of the Martian perihelion ([1], p. 108).

Direct measurements of their diameters have been possible only for the four largest ones, and even these measurements involve a considerable degree of uncertainty, as seen by a comparison of the values quoted in [1], p. 120; [2], p. 181; and [3], p. 25 to 31:

	<u>Minimum</u>	<u>Maximum</u>	
Ceres	690	770	km
Pallas	493	922	
Juno	195	240	
Vesta	374	475	

Much recent work on the asteroids is reported in [3].

The basic scientific interest in the asteroids, apart from that as practical examples for some problems of celestial mechanics, is centered about the questions of their origin and their composition. Of these two questions, we have, in a way, already some answers about the second one, since there are good reasons to believe that at least the majority of the meteorites falling on the Earth are of asteroidal origin*.

Concerning the origin of the asteroids (among which one should probably include the two tiny Martian moons and the minor satellites of Jupiter and Saturn), there are two main lines of thought:

1. They are the debris from an explosion of a larger planet (perhaps roughly the size of Mars) which may have been caused by radioactive overheating, or else the debris from a collision of two somewhat smaller planets which occurred a long time ago; or
2. For reasons unknown, the "normal" process of condensation of the material in our early solar system did not lead to the formation of a larger planet in the "gap" between the orbits of Mars and Jupiter, but stopped at the intermediate stage of the "planetesimals" which are our present-day asteroids.

According to the studies of G. P. Kuiper, one cannot unambiguously decide between these two alternatives. Some observational material supports fragmentation**, while some appears to point to condensation. It is, of course, probable that both processes have been active so that

* Not, however, the so-called "shooting stars" which are generally distinguished by a very low density, and are probably of cometary origin.

** The recently obtained pictures of the two Martian moons give the definite impression that they are chunks of rock and fragments of a larger body.

perhaps the majority of the asteroids are fragments of one or two larger bodies, while other asteroids are really "proto-planets" which are left over from a rather early stage of the development of our solar system.

If there are any such proto-planets among the present asteroid population, they are likely to be very different in their structure from the fragments of larger bodies which are essentially "big chunks of rock." Their material was never exposed to any significant heating, and also not to the high gravitational pressures which exist in the interior of larger bodies. That is, one would expect a small proto-planet to have an appreciably lower density than a fragment of a larger body, and this could be determined from an orbiter with little difficulty.

It is also a plausible guess that the looser surface structure of a proto-planet will result in more light-scattering, and therefore a larger albedo than one would obtain from a more compact solid rock, at least on the average. On the other hand, a very low albedo would at least give an indication that the body in question is of a heavier solid (e.g. basaltic) rock, and likely to be a fragment of a larger body.

By a fortunate coincidence, there are two among the four largest asteroids whose albedos are widely different; Ceres with about 0.032 and Vesta with about 0.252, an unusually high value for rocks. Of course, Ceres could be basalt, and most of the surface of Vesta could be an unusually light-colored granite, and both asteroids could then be fragments of a larger body.

Nevertheless, these two asteroids would be most interesting for a first more detailed study of a minor planet with an orbiter, Ceres as probably a fragment, and Vesta with a certain small chance that it could be something else.

According to the present, very preliminary, plans, the scientific instrumentation of the orbiter will now consist of:

- A.
 - 1. Imaging equipment
 - 2. IR radiometer, spectrometer and interferometer
 - 3. Radar
 - 4. Photometer
- B.
 - 1. Magnetometer
 - 2. Solar Wind Plasma Particle Detector
 - 3. Plasma Wind Sensor
 - 4. Meteorite detector

Of these instruments, those of the first group are for the study of the target asteroid, while those of the second group are intended for studies of the interplanetary environment on the way out to the asteroid, and during the orbiting mission around it. The magnetometer belongs perhaps to both groups. If the target of the mission was once part of a larger body which did have a magnetic field of its own, there may be some paleomagnetic remanence in it, although probably not very much.

For brevity, we consider here only the TV camera and the radar which, properly used, can give far more information on the target asteroid than merely the distance of the orbiter from it as a function of the time.

One would, of course, expect that the surfaces of both Vesta and Ceres show some cratering from meteor impacts, in the same way as we know it from the Moon, and have also recently seen it in the pictures of the two Marsina satellites. Because of the low escape velocities (200 to 300 m/sec for Ceres and 100 to 170 m/sec for Vesta) the debris from the larger meteorite impacts will be blown out into space with the exception of small particles that may be retained by cohesive forces. High resolution pictures of the crater forms will give indications of the hardness of the surface material. A rather hard material would then, of course, support the view that the particular body is the product of a disintegration of a larger object, while a softer surface would indicate that it could be a condensation product; i.e., a proto-planet.

Another hint at the origin of the asteroid can be obtained from the reflection of the radar pulses, since they give an indication of the dielectric constant of the surface material.

Depending on what one finds in the first pictures and from an analysis of the details of the radar reflections, one may want to make some changes in the strategy of the optical investigation of the asteroid from orbit, such as to take a closer look at certain particularly interesting surface parts. It seems to the writer that this can be done by command from Earth, since an orbiter will remain around the body for a rather long time. Essential is then only that the instrumentation of the orbiter has enough flexibility to do the various things one might want it to do.

The preceding comments on the TV pictures were concerned with the details of the asteroids surface, and with what can probably be learned from them. Also important is the general form of the body which is unlikely to be as spherical as a larger planet with a stronger gravity field. An indication that both Ceres and Vesta may not be quite spherical, and Vesta less so than Ceres, is given by the observational fact that both asteroids show small periodic fluctuations of their brightness, with a maximum amplitude of 0.04 stellar magnitude and a well-determined period of 9^h05^m in the case of Ceres, and with the rather large maximum amplitude of 0.13 and a period which is variously given as between 5 and 6, or between 10 and 12 hours in the case of Vesta ([1], p. 121).

The small brightness fluctuation of Ceres may simply come from small differences in the surface reflectivity of a rotating almost spherical body. And if this body is then also hard rock, one may guess that it was formed from the hot interior material of a disintegrating larger body as a kind of still somewhat liquid drop which became then spherical under its own gravity, and later cooled and solidified to its present state. If this is so, the density

of Ceres could be rather high, and it may contain more iron than the average asteroid. It could then even have a small frozen-in magnetic field.

Before going into an orbit around Ceres, it could be useful to have a rough idea of the orientation of its axis of rotation, so that one can put the orbiter into a roughly polar orbit which would give a better coverage of the entire surface of the planet over a period of time. The writer would therefore like to suggest the taking of some pictures of the planet as soon as one can get some detailed resolution during the approach, and their on-board evaluation by a computer with some pattern recognition capability and some "intelligence."

The same rough on-board determination of the rotation will also be desirable for a Vesta mission, of course. It may be somewhat more difficult, since Vesta is likely to be more aspherical than Ceres, and would then show an appreciable wobbling of its instantaneous axis of rotation. But one does not need to know the axis with a very great accuracy to get a good overall surface coverage of a body with a diameter of about 400 km from a distance of approximately 1000 km from its center. An orbit with e.g. 60° inclination to the "mean equator" of a somewhat wobbling body is then still a "practically polar" orbit, and good enough for our purpose.

We may, however, mention that if Vesta should show an appreciable wobbling, we may want to take more pictures of it than we need to study only its surface features. We can then determine its three principal axes of inertia from the wobbling, and get some idea of its internal mass distribution. The decision on what would be needed can, of course, be made on Earth since there will be ample time for doing it.

The spacecraft will also make some measurements of the interplanetary environment while on the way from Earth to its target, and they will also benefit from a certain adaptability of the spacecraft to occasional sudden changes in its environment (solar flares, passage through a micro-meteorite stream, etc.).

II. COMETARY MISSIONS, ENCKE AND HALLEY

We shall consider a rendezvous mission to Encke's comet with a launch date in 1982, a flyby mission to the same target with launch in August 1980, and a flyby mission to Halley's comet with launch in May 1984.

A review of some of the astronomical and space science literature concerned with comets ([4], [5], [6]), indicates that the least well understood problems about the comets are those concerning the structure, the mass, and the size of their nuclei. These are followed by the question of the gradual disintegration of the nucleus by outgassing and ejection of solid particles due to solar heating about which a great deal is known from spectroscopic observations of their luminescent emanations, but where one would like to have some quantitative data from direct in situ measurements for comparison with the telescopic results. Other less important questions are the detailed gas and dust particle dynamics in the coma and the tail, the relative importance of their two conceivable driving forces (solar light pressure and dynamic pressure of the solar wind), and the mechanism which produces occasionally observed weak radio signals from parts of the tail, and a few others.

The nucleus of a comet is a small region of its head, surrounded by an often rather large luminous cloud of gases and dust (coma), which appears in a telescope of sufficient resolution as a somewhat fuzzy star whose light, as shown by its spectrum, is essentially reflected and scattered sunlight. Not all comets have a well-defined nucleus, and some of them have two or more distinct condensations of material in their heads.

The currently best model for a cometary nucleus is that of a cloud of small to moderate sized solid particles of dirty ice, i.e., frozen water, ammonia, carbon dioxide, methane and similar substances with inclusion of small mineral particles of various compositions. An earlier "monolithic"

model as a big chunk of partly or mainly volatile material is increasingly difficult to support. Its outgassing would be far less than that of a particle cloud into which the solar radiation can readily penetrate to a considerable depth.

The containing force of this cloud is then its own rather weak gravity. Its particles are constantly but slowly moving around in it, with probably frequent collisions, in the same way as the molecules of a gravitating gas cloud. As a whole, this cloud may or may not have an appreciable rotation.

It is clear that such a particle cloud cannot exist for a very long time, if its mass is too large. To balance the greater gravity, its "gas pressure," i.e., the random particle velocities, would then also have to be larger, and their collisions would become more violent. This will shatter and heat the particles, with a corresponding loss of most of their volatile material, and with simultaneous and subsequent loss of the heat by radiation into space. Unless such a large cloud is too rapidly rotating, it will then condense into a smaller and more compacted body with relatively little residual volatile material, and this could be the process of the formation of "proto-planets" and later larger planets. The comets never made it beyond the cloud stage, because they were too small.

There is general agreement that the masses of all comets are very small by astronomical standards. Numbers on their masses, on the other hand, are difficult to come by. The most reliable determination of a comet's mass was due to a fortunate accident, when the nucleus of Biela's comet split into two parts during its apparition in 1846. Their mutual perturbation indicated a combined mass of 4.2×10^{-7} of the Earth's mass, or 2.5×10^{18} kg. This is less than 1 percent of our previous lower estimate of 3.5×10^{20} kg for the mass of the largest asteroid, Ceres. Other less well founded mass estimates were obtained for Halley's comet, $M_H \sim 3 \times 10^{16}$ kg, and for three other comets

whose minimum masses ranged from 5×10^{13} to 7×10^{14} kg. In addition, it has been possible to obtain upper limits for the masses of some twenty comets which happen to pass rather closely to the major Jovian satellites without causing a perceptible perturbation of their motion. These upper limits range from a maximum of 7×10^{19} kg to a minimum of 3×10^{14} kg ([14], p. 37-39).

A similar large uncertainty exists for the diameters of cometary nuclei which seems to be in general between the orders of 1 and 10 kilometers. Some specific estimates of diameter ranges for a number of comets are given in [4], p. 38, but these include neither Encke's nor Halley's comet.

A typical comet model is found in [4], p. 166-67. While it is probably the best we can have at the present time, it gives only a very rough guidance for planning a cometary mission.

In consideration of these large uncertainties about comets in general, and about the two specific target comets Encke and Halley in particular, and in consideration of the rather appreciable round-trip communication times, it seems to the writer that a self-contained on-board terminal navigation system could be even more desirable than for an asteroid mission.

Without an on-board terminal navigation system it will still be possible to fly the missions with a good chance of obtaining new and interesting results.

But the spacecraft has then to stay farther away from its most interesting study object; i.e., from the comet's nucleus, for reasons of its own safety, especially in the two flyby missions where the relative velocity between the spacecraft and the nuclear cloud is substantial. Around this cloud, there will be quite a few and perhaps rather large particles (1 cm size or greater) at a considerably greater distance from its center than its nominal radius. It is undesirable to take too much of a chance for the spacecraft to collide with them at even "only" a few hundred m/sec. In the Encke rendezvous mission,

The velocity of the spacecraft must be adjusted much earlier to that of the comet's nucleus, and some mission time will be lost of having to "inch in" towards the nucleus from a longer distance.

Operation during the rendezvous, at the present time expected to last for three months or more, cannot be planned in advance, but has to be decided when the spacecraft is rather close to the nucleus, so that it is possible to get a good idea of its mass and its dimensions.

Two strategies are available for rendezvous. If the comet has an appreciable mass, it may be desirable to put the spacecraft initially into a roughly circular orbit at a distance of around 1000 km from the center of the nucleus. The procedure from then on is to maneuver the spacecraft gradually closer to its target, if it appears that this can be done without an unacceptable hazard.

If, on the other hand, the mass of Encke's comet is small enough it might be preferable to choose a mode of operation in which the spacecraft is lingering around its target in practically the same orbit around the Sun, occasionally changing its velocity relative to the comet's nucleus by very small impulses.

III. OUTER PLANET ATMOSPHERIC PROBES

From the point of view of adaptive system engineering, the most important features of all missions into the atmospheres of the major planets are their short durations, the long round-trip communication times, and the uncertainties about the atmospheric environment.

Even to the flyby spacecraft, the round-trip communication times are rather long. Takeing a Jupiter orbiter at a distance of 200 planetary radii $\approx 1.4 \times 10^7$ km as a typical example, the round-trip communication time is about 1-1/2 minutes. This may still permit some control of the probe from the

relay station if there are communication difficulties which can be caused by higher than anticipated NH_3 content of the atmosphere or by turbulence fading.

In such cases, the relay station could send a command to the probe to concentrate on the most important measurements and to transmit with a reduced bit rate.

To do this job "intelligently," the "brain" of the relay station has to distinguish between communication trouble from turbulence fading which is likely to level off as the probe goes down more and more, since the highest turbulence levels are to be expected near the cloud level (condensation instabilities), and NH_3 and to some extent also H_2O absorption losses which will get much worse with the depth of probe penetration, because of the increased pressure broadening of the absorption lines in the microwave spectrum. If absorption is the trouble, the "brain" has therefore to anticipate the further deterioration of the communication link, and to initiate a sequential reduction in the data flow until, finally, only the most basic data, such as pressure and temperature, can be transmitted with an adequate reliability to the practical end of the mission.

Most other decisions about changes in the probe experiments will probably have to be made in the probe. To see what they are likely to be, we consider at first the preliminary list of instruments which is the same for all four missions. They are:

- A. Imaging (TV); IR limb scanner; magnetometer;
- B. IR radiometer, spectrometer/interferometer; UV spectrometer, gamma-ray spectrometer; water detector; pressure and temperature sensors; photometer; gas chromatograph; accelerometer.

The instruments of the first group are clearly intended for use prior to the entry of the probe into the sensible atmosphere, with the exception of the magnetometer which one may want to use also further down.

Considering of group A only the TV camera of the probe, the relay station (orbiter or flyby) will also have a TV camera which will be able to take low resolution pictures of the entire disk of the target planet from a considerable distance. If its "brain" can then perceive in these pictures some unusual or interesting features, it could send a command to the probe to take a closer look at them, rather than following the program of picture taking which was originally planned for the approaching probe. Alternatively, the "brain" of the probe itself could also have the capability to change the original picture taking program, if it notices, e.g., a region of unusually high contrast, in one of its pictures. It could then decide to lock the camera to this region, and to take more pictures of it to get a higher resolution as the probe comes closer to the cloud "surface" of its target planet.

Considering now some of the instruments of group B which will be used while the probe is descending through the atmosphere after successful entry, it is probable that the photometer and the UV spectrometer will lose their usefulness at a certain depth below the cloud tops when there is no longer enough sunlight available to get a meaningful reading. The "brain" of the probe should recognize this and turn them off, so that more of the power reserve and more of the communication capability can be utilized for the other experiments.

A similar situation could exist for the water detector, but it is somewhat more complex, and one could lose some valuable information by a decision which is too hasty.

If water is the only condensable component in a planet's atmosphere, as on Earth, and if we are dealing with a very deep and well mixed atmosphere, as is likely to be the case for all the major planets, we will find very little water above the cloud level which acts as a cold trap, and a practically constant water content below the clouds. Once we find that a constant water

vapor percentage has been reached during the descent, we would not expect it to change any more with increasing depth, and we could terminate our experiment as no longer interesting.

In the presence of other condensables which can form hydrates, we have, however, to consider the possibility of lower "cold trap levels" for these hydrates, and we can terminate our experiment only if we can be reasonably sure that the temperature is high enough, e.g., 300 or 350°K, to practically exclude the existence of any "hydrate traps" for the water vapor at greater depth.

The pressure and temperature sensors will certainly be operated during the entire descent of the probe through the atmosphere, until it eventually fails due to the rising pressure or due to excessive heating. In general, one would here expect a gradual and regular increase of both P and T, and one could monitor it with the transmission of relatively few data points, e.g., every minute or so. Any irregularity in these increases of pressure and temperature would, however, be interesting, since it would indicate vertical motions (large scale turbulence) in the atmosphere which will also be sensed by the accelerometer. The "brain" of the probe should be capable of recognizing such deviations from the expected regular increase, and should then increase the transmission rate of the (P,T) data at the expense of other data, if it considers the change as important enough.

As our last example for the possible use of an adaptive system in Major Planet Atmospheric Probes, we consider the operation of the gas chromatograph. While one may see only a very remote chance for the existence of any "life" as we know it in their atmospheres, there is a rather good chance for some, and perhaps even for a rich pre-life organic chemistry in, especially, their clouds, because of the strongly reducing character of their atmospheres. And, if a complex pre-life chemistry should exist in the clouds, its detailed study

would be of great importance for confirming or modifying our present ideas on the origin of life on Earth, and on its possible origin elsewhere in the universe.

The existence of any complex organic chemistry in the clouds of the major planets should show up very soon in the results from the gas chromatograph, simply by the detection of molecules with a molecular weight of, say, more than 60 or 70. If one detects such heavier molecules, one would, of course, continue the search for even heavier ones in necessarily fewer, but longer-lasting experiments. If there seems to be a practical cut-off at $M \sim 60$, there is little use for these extended experiments, and one should make a greater number of shorter ones to obtain a good altitude resolution of the variations of the abundance of the more common atmospheric constituents.

IV. OUTER PLANET ORBITER MISSIONS

For uniformity, we assume that the scientific instrumentation is the same in all four missions and that it consists of:

- Imaging
- IR radiometer, spectrometer/interferometer
- IR limb scanner
- UV spectrometer
- Magnetometer
- Solar wind plasma detector
- Plasma wind sensor
- Charged particle telescope
- Mass spectrometer
- Neutron flux detector
- Solar x-ray monitor
- Photometer
- Meteorite detector
- Radio receiver

Each of these missions serves three different purposes.

1. On the way out from Earth to the target planet, the spacecraft will make measurements of the interplanetary environment (magnetic fields, solar wind, influence of solar activity at great distances from the Sun, meteorites, etc.).

2. Once in orbit around the planet, the spacecraft will continue these measurements especially to see how the planet and its magnetic field (if it has one of any consequence, which is so far only established for Jupiter) modify the interplanetary environment. It will then also observe phenomena in such a magnetic field and in trapped radiation belts which may be associated with it.
3. From its orbit, the spacecraft will also observe the planet itself: Its cloud cover and any changes in it with a TV camera, its surface temperatures by IR mapping, the composition of its upper atmosphere by UV and IR spectroscopy.

The following comments on these three parts of the orbiter missions will be restricted to a number of phenomena which are of considerable scientific interest, but are either only likely to be observed in a specific mission, or else will be observed almost certainly, but at unpredictable times and locations. In other words, we wish to restrict our comments to those aspects of the missions where their scientific return is likely to benefit from a certain flexibility and adaptability of the measurement program.

We consider the three parts of the mission sequence, starting with

1. Transit Flight from Earth to the Planet

During this time, we expect to observe a gradual change in the interplanetary environment as the spacecraft moves farther out: decreases in the strength of the interplanetary magnetic field and in the particle density of the interplanetary plasma, etc. In the Uranus and Neptune missions, we expect also to observe some changes in this environment during the Saturn flyby which will be used for gravity assist in the Uranus mission and during the flyby of again Saturn and later Uranus which will be used for the same purpose in the Neptune mission.

Without being able to predict when and where it will happen, we expect, however, also to observe occasionally some significant changes in the spacecraft's environment, such as when the spacecraft passes through the remnants of an outgoing gas cloud from a major solar flare, or through a meteorite stream. Since these events would be of special interest, it would be useful, if a computer "brain" in the spacecraft could recognize them (and also, by the way, the improbable but possible passing through the tail of a comet), and if it could then step up the normally relatively slow rate of its interplanetary measurements, and report these events to Earth in greater detail, when the time comes for the data transmission.

A particularly important and unresolved question about the interplanetary space is, how far the solar wind reaches outward from the Sun, and what happens in the probably rather irregular transition region (associated with a magnetic shock) between the solar wind plasma and the surrounding interstellar medium whose distance from the Sun may well fluctuate appreciably with time.

Consider now the second objective of Outer Planet Orbiter Missions:

2. Study of the Planet's Environment from Orbit

In this part of the program, the plasma density measurements, the magnetic measurements, the meteorite detection, and the other experiments during the transit flight will continue for the anticipated lifetime of the orbiter and their scientific return is again likely to be substantially increased by an on-board capability to recognize transient phenomena for a more detailed study.

Of particular interest is the change of the environment by the vicinity of a rather massive body, in particular by its gravity field which affects meteorites, and even more so by its magnetic field, if it has one.

If the planet has a magnetic field of consequence, it is also likely to have some trapped radiation belts, even if the solar wind should not reach out to its orbit. At least the "neutron albedo" process from the interaction of cosmic particle radiation with the atmosphere (see [5], p. 558) should still supply about as many particles per unit surface area to the belts as it does on Earth, and there may also be some particle injection into them from the interstellar plasma.

In this case, one would have a great wealth of phenomena to study, both "static" or but slowly variable ones for which the appropriate changes in the measurement program can be made by commands from the Earth, and highly transient ones such as the Jovian decametric radio bursts to which the orbiter would have to adjust itself for obtaining anything more than unconnected purely accidental instrument readings.

A rough estimate of the shock location can be made for Jupiter whose equatorial surface field is around 5 gauss. Equating the energy density in the solar wind, of the order of 10^{-11} watt sec m^{-3} at the Jupiter distance of ~ 5.5 a.u., to that of a magnetic field ($= B^2/2\mu_0$), one obtains $B \sim 5 \times 10^{-9}$ volt sec $m^{-2} = 5\gamma$. With the inverse cube law for the decrease of a dipole field, one finds then a shock stand-off distance of around 45 planetary radii.

For the other planets, we have no basis for any quantitative estimates. But we would have to be prepared for making such magnetic and field-particle interaction measurements in the mission, if we find after

arrival in orbit that there are interesting phenomena to observe. On the other hand, we should be able to re-direct the orbiter's program, if we find that there are no such effects of great interest.

Doing this re-direction by command from Earth is probably satisfactory. A delay of even a few days will not matter very much in comparison with an anticipated orbiter life of 400 days.

Turning now to the third and last, but not least, scientific objective of an Outer Planet Orbiter Mission:

3. Study of the Planet Itself from Orbit

We may start our discussion with the optical imaging system, i.e., with the telescopic TV camera whose purpose it is to give us a great number of pictures of the cloud top "surfaces" of the four planets, so that we can obtain from their study, and from the study of simultaneous IR mapping of the cloud top temperatures, a better idea of the dynamics and thermodynamics of the cloud top level than we have now. The temperature mapping will also give us a better estimate of the magnitude of Jupiter's internal heat source (the planet seems to radiate about twice as much energy into space as it receives from the Sun, probably due to a release of gravitational energy by a very slow contraction), and it should give us an answer to the question, if any one of the other major planets has such an appreciable internal heat source.

The larger cloud patterns that we can observe with terrestrial telescopes are persistent enough to permit a very accurate determination of the rotation periods of the planets from many observations, and even enough to give such details as the faster rotation of Jupiter's equatorial zone. From the orbiter pictures and thermal mapping we can, however, expect a considerably greater resolution of details which will

presumably change more rapidly, and much too rapidly for controlling the picture taking and the thermal mapping from Earth.

This would indicate that more interesting details could be obtained with evaluation of the pictures and the mapping results in the orbiter during and following the measurements, and by letting the orbiter's computer decide how to modify the measurement program.

Regardless of how much artificial intelligence and automatic adaptability can be used in all three parts of the outer planet orbiter missions (or for that matter in any other space missions of sufficient duration), it will be highly desirable that their program have a certain flexibility and can be changed by commands from the Earth, if this is called for by the incoming results.

If an adaptive system is used in such a mission, it would also be a good idea to design the computer so that its program can be changed to at least some extent by commands from the Earth. Because of the substantial uncertainties on what can be expected on and around these far-away celestial bodies, it is impossible to know in advance, how good the various decision criteria in the computer program will turn out to be in practice, and it should be possible to modify them, if it appears from the incoming results that the computer's judgment on some situations is likely to be a misjudgement.

V. INNER PLANET ORBITER MISSIONS (VENUS AND MERCURY)

From the point of view of adaptive system technology, the problems in these missions are very similar to those which occur in the outer planet orbiter missions.

On their way from Earth to their target planets; i.e., for about five months to Venus, and for about 20 months to Mercury, the spacecraft will make measurements of the interplanetary environment.

Apart from a slow and regular change of the instrument readings as the spacecraft get closer to the Sun, one will then have to expect a number of transient events at unpredictable times, e.g., when the spacecraft pass through the outward moving plasma cloud from a solar flare, or through a micrometeorite stream from a disintegrating comet. It would then clearly be desirable if the computers could recognize an appreciable change in the instrument readings to step up the rate of their measurements.

The same measurements will be continued while the spacecraft are in orbit around their target planets, i.e., for an anticipated three months or more around Mercury, and for an anticipated eight months or more around Venus. Apart from continuing to monitor solar and interplanetary events, the scientific objective is then also to determine how the interplanetary environment is changed by its interaction with the nearby planet.

Adaptability for operation of the visible imaging and IR and UV mapping of Venus is similar to that for the outer planets, except that the shorter communication time and higher data rate make control from Earth more feasible.

Optical imaging and thermal mapping of Mercury is very similar to the optical and thermal mapping of Mars. All indications are that one can obtain as good results from Mercury imaging and thermal mapping as from doing the same things on Mars, without the use of an adaptive system.

In the radar mapping of Venus from orbit, the situation may be somewhat different. Probably not, as far as the mapping itself is concerned, but because of atmospheric influences.

We know from the exploration of the planet with Earth-based radar that its surface is generally smoother than that of the Moon, but has some "features" which may be mountains and/or areas where the surface is unusually rough on the scale of the wavelength of the radar beam ([9], pp. 128-29; [8], pp. 314-19). These results which, for geometric reasons, could only be obtained for the lower

latitudes of the planet's surface, have become considerably more detailed in the recent past, and will continue to improve until the time the mission can be flown, some nine years from now. What we expect from this mapping is then better results than we can get from Earth for the lower latitudes, and new results for the higher latitudes we cannot observe with radar from here. If there were no atmospheric perturbations of the radar propagation, it seems that one could obtain the results one wants with an essentially pre-planned measurement program which can be somewhat changed by commands from Earth if there seems to be a need for it.

Unusually strong atmospheric turbulence in certain areas and at certain times could, however, interfere with the propagation of the radar beam through the atmosphere, by causing signal scintillations known as "turbulence fading." If such erratic changes of the reflection from the same surface area should occur during the mission, it would be useful if the "brain" of the orbiter could recognize them and could adjust the measurements to them. It should then also report their occurrence separately since they are of interest for a better understanding of the dynamics and thermodynamics of the Venus atmosphere.

Apart from these signal fluctuations, the returning radar pulse may also contain a faint echo from the clouds, preceding that from the reflection on the solid surface, especially in places where the clouds are thick enough to produce appreciable rain. Whenever such rain echo should occur to an unambiguously detectable degree, it would again increase our understanding of the Venus clouds if the "brain" of the orbiter could recognize it, and would then report this phenomenon separately at the times of the data transmissions.

VI. VENUS BUOYANT STATION

Because of its rather long duration of around three months, the mission of a Venus buoyant station has some similarities to the previously considered orbiter missions to the outer or inner planets as far as the usefulness and desirability of adaptive systems in the mission is concerned.

The basic scientific mission of the buoyant Venus station is the detailed study of the planet's cloud cover, in particular its composition, particle size and particle density, its optical properties and its probably somewhat variable thickness, the winds and other meteorological phenomena (rain, etc.) in it, and the conceivable, although improbably existence of some form of primitive life in it.

Along with this primary objective, the station will also obtain some detailed information about the parts of the planet's surface over which it drifts during the mission, in particular on elevations, roughness, and dielectric properties of the surface from radar altimeter data.

Technical details on the design of the buoyant station are given in a recent Martin Marietta report [9]. It is essentially a superpressurized balloon, with hydrogen as its carrier gas, which will seek and maintain a certain design pressure level, such as 50, or 500, or 1200 mb, and which carries its scientific payload and its auxiliary equipment on a gondola. Communication to Earth will be through an orbiting relay station which accepts and stores the data from the balloon when it passes over it, and transmits them to Earth when it is in a favorable position for doing so.

A preliminary list of the scientific instrumentation could be:

IR radiometer, photometer, nephelometer, as optical instruments;

Water detector, mass spectrometer, gas chromatograph, and wet chemistry for determining the composition of the clouds;

Pressure and temperature sensors, an accelerometer, and a radar altimeter;

Atmospheric electricity detectors; and

Biology experiments.

The wet chemistry experiment should include a determination of the P_H value of liquid cloud droplets which may be quite low (= strongly acid) because of the spectroscopically detected HCl traces in the atmosphere above the clouds.

Of all the experiments which are to be made in the mission, the biology experiment is clearly the most speculative one. It is also the most difficult one to design since we have no good idea of what a biosphere in a probably rather acidic cloud layer would be like. The only reasonably promising approach would be a very basic one, such as looking for catalytic actions of enzymes in certain chemical reactions involving the transfer of heavy oxygen, O_{18} .

Even then, the experiment would have to be made at P_H values quite close to that at which any such enzymes are active. Decisions would also have to be made on the size of the cloud material sample to be taken, on the duration of the experiment, and probably on a few other things.

That is, the experiment must be designed with a certain flexibility, and the station must be given some detailed instructions on how (and probably also when) to conduct the experiment, in order to have the greatest chance for detecting any biological activity on Venus, should it exist.

The most promising course of action can here clearly only be decided upon after the station has been operating in the Venus clouds for some time, and after quite a bit has been learned about the details of the cloud chemistry from the various chemical and physico-chemical experiments.

Because of the complexity of the situation, it seems that these decisions should be made by human judgement after an extensive study of the results of

the chemical experiments from; e.g., the first week of operation. There is clearly time enough for doing this, and for sending then the appropriate instructions for the biological experiment to the station.

Other examples where a change or redirection of the scientific program from the Earth would be indicated are when the results from some of the experiments turn out to be repetitive while others show a greater variation.

If it turns out that the chemical composition of the cloud material is rather simple, water, some HCl and HF, and a little FeCl_3 with practically no organic molecules, and that it is practically the same at all times and phases, the station would then be instructed from Earth to de-emphasize the chemical experiments, and to concentrate on "meteorological" measurements where there may be more interesting things to observe.

It may be necessary to re-emphasize the chemical experiments again if there is an appreciable change in the physical conditions around the station which could affect the chemistry of the clouds.

One such example is when the balloon drifts across the terminator where there is the possibility of photo-chemical processes on one side, but not on the other side. Since the time of occurrence of this event can be predicted reasonably well in advance from the tracking data, the situation can probably be dealt with by commands from the Earth. Alternatively, an increased emphasis on the chemical experiments in the station itself can be triggered by the change in the photometer readings, and this would not be very difficult.

Another example where it might be desirable to do a few more, and also more elaborate chemical experiments would be when an unusually strong electrical activity is observed around the station, or not very far from it. There is then, however, not time enough to make changes in the experiments from Earth, and any decision to do so has to be made by a computer in the station.

Considering now the optical experiments of the mission (of which those using sunlight can, of course, only be made during day time), it seems likely that the instrument readings will always show a certain variability: the cloud layer above a balloon locked to a certain density level in the atmosphere will be thicker at times and thinner at other times, and any unusual change in the instrument readings should trigger an automatic response for studying the event in greater detail, and also for paying more attention to some of the other experiments (increased electrical activity in a thick cloud above the balloon).

It is likely that the radar altimeter data will show strong fluctuations in certain areas, and little change in other areas. In some cases, it is possible to predict when the station is likely to drift over a known surface feature, and the station can be instructed to pay particular attention to it. In other cases, for instance, when the station is at higher latitudes where surface features cannot be observed by Earth-based radar for geometric reasons, it is necessary to rely on an automatic response to obtain the structure of these features in greater detail.

VII. VENUS LANDER

Because of the rather short lifetime of a Venus lander there will not be enough time to make any changes by commands from the Earth. The basic mission of the lander is to obtain information on the structure and composition of the planet's surface at the landing site, on the state of the atmosphere immediately above it, and on any seismic activity in the interior of the planet.

For carrying out its mission, the lander will have some of the following scientific instruments: imaging, gamma-ray spectrometer, x-ray fluorescence spectrometer, magnetometer, pressure and temperature sensors, nephelometer,

photometer, anemometer, gas chromatograph, seismometer, accelerometer, x-ray diffractometer, alpha-backscattering, wet chemistry, and age dating.

Considering at first the imaging experiment itself, there are substantial uncertainties about the conditions under which the pictures are to be taken.

If the landing site is on the sun-lit side of the planet, there could be enough visible sunlight on the surface to use it for the illumination. It will, however, be a diffused light which reduces the contrast in the pictures, and it can not be very much, since it has been calculated that due to Rayleigh scattering in the dense atmosphere alone not more than 5% of the incident sunlight could penetrate to the surface. The use of artificial illumination (flares and/or incandescent lamps) seems therefore to be the better bet.

The natural illumination will be measured with a photometer, and from a knowledge of the artificial light sources it is a simple calculation to find the lens opening which is needed.

Another area of great uncertainty is the seeing conditions on the Venus surface which determine to what distance one can hope to get any details in the pictures. It is quite possible that the lowest parts of the Venus atmosphere contain suspended dust. How much of it there is is unknown, but one will get an indication of the transparency of the surface atmosphere from the reading of the nephelometer shortly after the landing. Depending on what the situation is found to be, a relatively simple computer can then make a selection of one of several more or less ambitious pre-established picture taking programs. It is also possible that the landing of the vehicle itself could stir up a dust cloud.

What one will see on these pictures of the Venus surface at the landing site is anybody's guess. It could be a rough surface from a lava flow, or a basically smooth surface with some stones lying around on it. It could also be a very smooth surface, showing no structure whatsoever on a scale of, e.g., more than a millimeter.

Supposing now that the camera can "see" far enough, at least a few meters or a few tens of meters (for which, in the opinion of the writer, there is a good chance), it would be interesting to take a number of pictures for a panoramic view of a rough surface for as far away as details can be recognized. In addition, it would be desirable to take a few close-up pictures with some magnification, and probably also a few surface pictures through a microscope with substantial magnification.

On the other hand, there would not be much point in sending to Earth a panoramic view of a flat and very smooth surface without any recognizable details. In this case the lander should concentrate on magnified close-ups and on microscopic pictures where more details can be expected.

To take care of this definite possibility, it may not be so very difficult to design an adaptive system which first takes a look around for interesting things and decides then what to emphasize in its picture transmission to Earth: a panoramic view of the surface around the lander, or more close-ups and microscopic pictures.

It is definitely desirable to take a picture of the area quite close to the lander where the various experiments on the chemical composition of the surface will be performed with some flexibility on where to take soil samples in this area and where to bring sensors for alpha-backscattering and x-ray fluorescence into contact with the surface, or let them penetrate a little into it, an on-board analysis of the picture for the location of any non-uniformities in it could be valuable. Otherwise, a predetermined rigid search pattern must be used in which it would be easy to miss a small spot where interesting information is available.

Whether or not there is any significant seismic activity on Venus is unknown. With respect to the three types of sources of ground tremors, shallow earthquakes with an epicentric depth of less than around 70 km, deep-rooted

earthquakes with epicentric depths of up to 700 km in rare cases, and volcanic activity, it can be said that shallow earthquakes which release about 85 percent of the total seismic energy on Earth are very probably more diffuse and less violent on Venus where the higher surface temperature makes the rock layers below the surface more plastic so that it is more difficult to build up very high subsurface stress levels. Deep-rooted earthquakes whose causes are poorly understood may well occur about as often, or rather as rarely, as they do here. Volcanic activity which is generally a very minor and local source of ground tremors may exist on Venus. The spectroscopically detected traces of the highly reactive gases HCl and HF in the upper atmosphere seem to support this view, since both gases occur in terrestrial volcanic emanations.

Under these circumstances, there is but a small chance to detect a seismic event of appreciable magnitude during the probe lifetime. Should it occur, however, it would be of very great scientific interest and it should be reported to Earth with the greatest amount of detail that can be obtained from the seismometer. It may even be desirable to interrupt the taking and the transmission of surface pictures to take as much advantage as possible from the unique opportunity to get some information on the interior structure of the planet.

Should no such event occur during the lifetime of the lander, a low-level seismic background will probably be observed and it would be adequate to transmit a few samples of a minute or so duration.

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APPENDIX B
ORBITAL AND FLYBY GEOMETRY

ORBITAL AND FLYBY GEOMETRY

The relative position of the spacecraft with respect to the planet is of interest in determining the science value. This is done for both the selected orbital and also for the flyby missions. Timing marks labeled in hours show the time histories.

For the flyby cases the relative motion is a function of the excess hyperbolic velocity (V_{HE}) and the radius of the hyperbolic periapsis (R_p). In general the V_{HE} can not be altered for a given mission opportunity and is a result of the interplanetary transfer in relation to the target planet. The radius of the hyperbolic periapsis is variable and as this radius is reduced the turning angle is increased. For some of the missions a close periapsis passage may not be desirable because of radiation hazards (Jupiter) or physical hazards (rings of Saturn).

The orbital geometries indicated were selected from previous studies where available, and where not, a fairly high eccentricity was chosen to minimize the orbit insertion requirements for these missions. Depending on the desired payload for these orbital missions and the availability of propellants for the orbit insertion maneuver, a lower period orbit with a lower apoapsis radius might be possible.

The circular orbit for the Neptune mission is the result of a proposal to use nuclear electric propulsion and spiral into orbit with a low thrust level. Elliptical orbits are equally feasible with negligible differences in payload capability. No attempt was made to optimize the trade-off between payload and orbital eccentricity since specified mission goals and spacecraft weights are not defined.

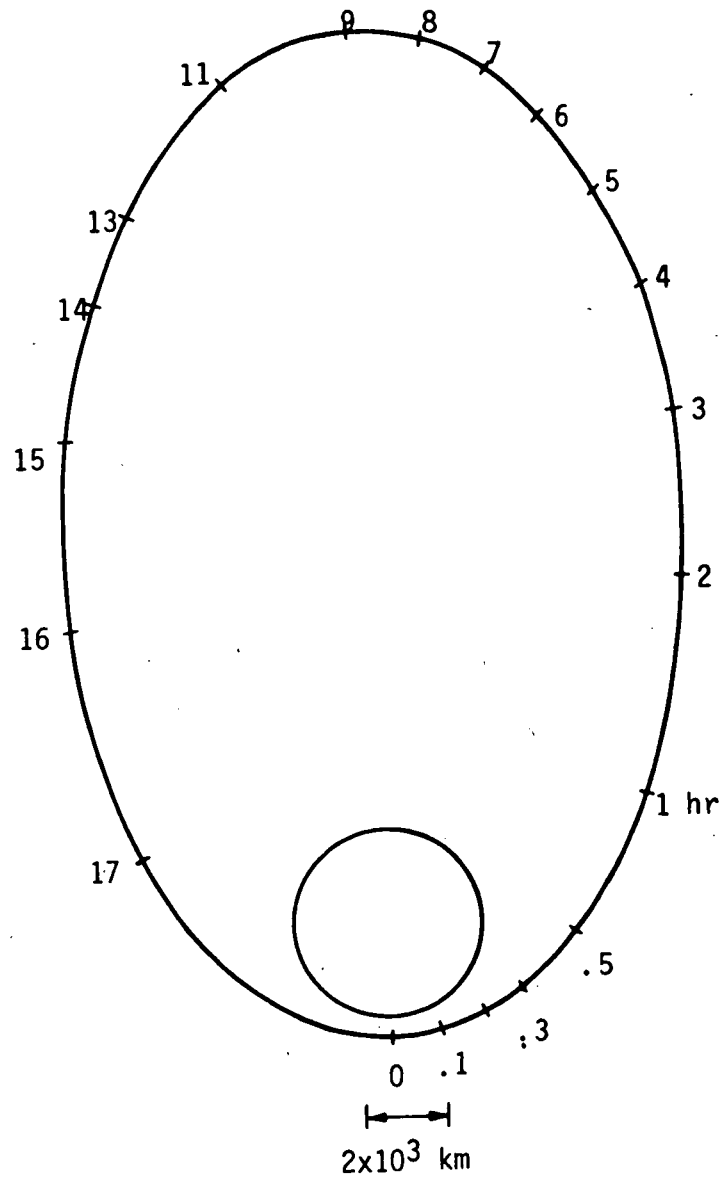


Figure B-1 Mercury Orbit

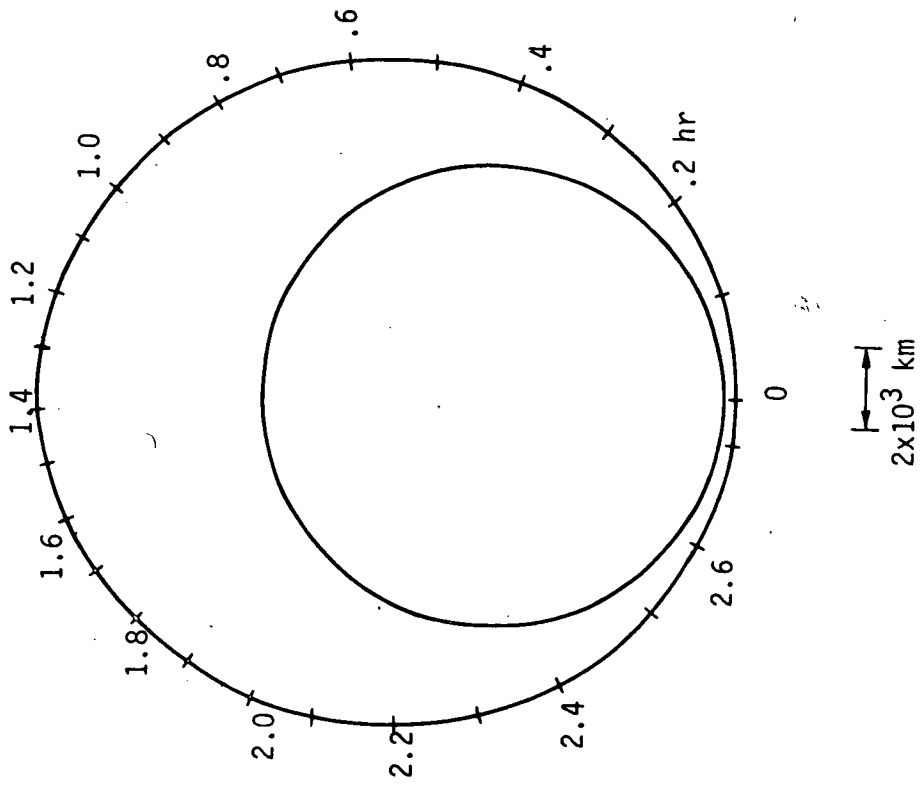


Figure B-2 Venus Orbit

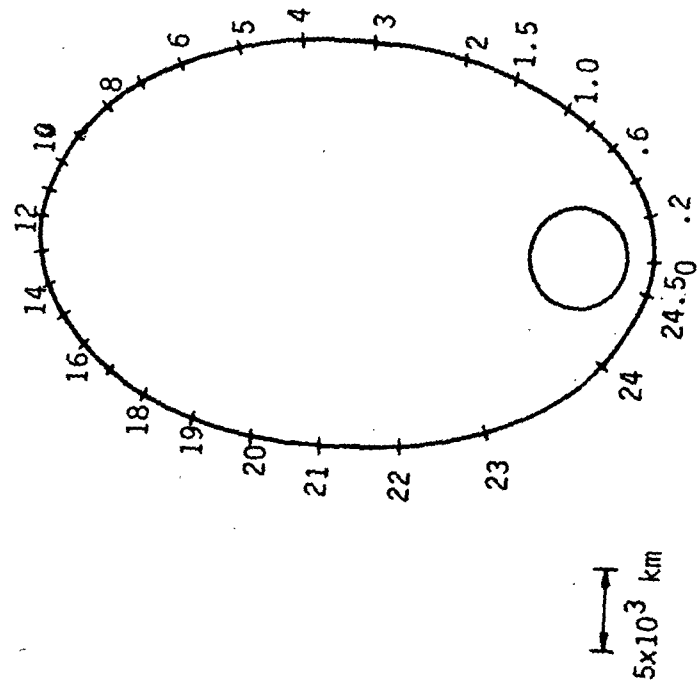


Figure B-3 Mars Orbit

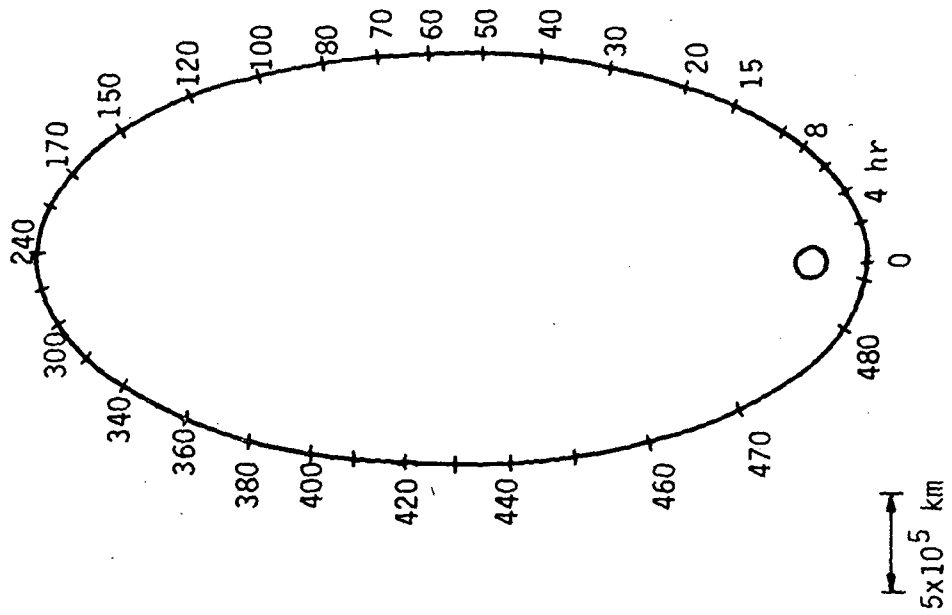


Figure B-4 Jupiter Orbit

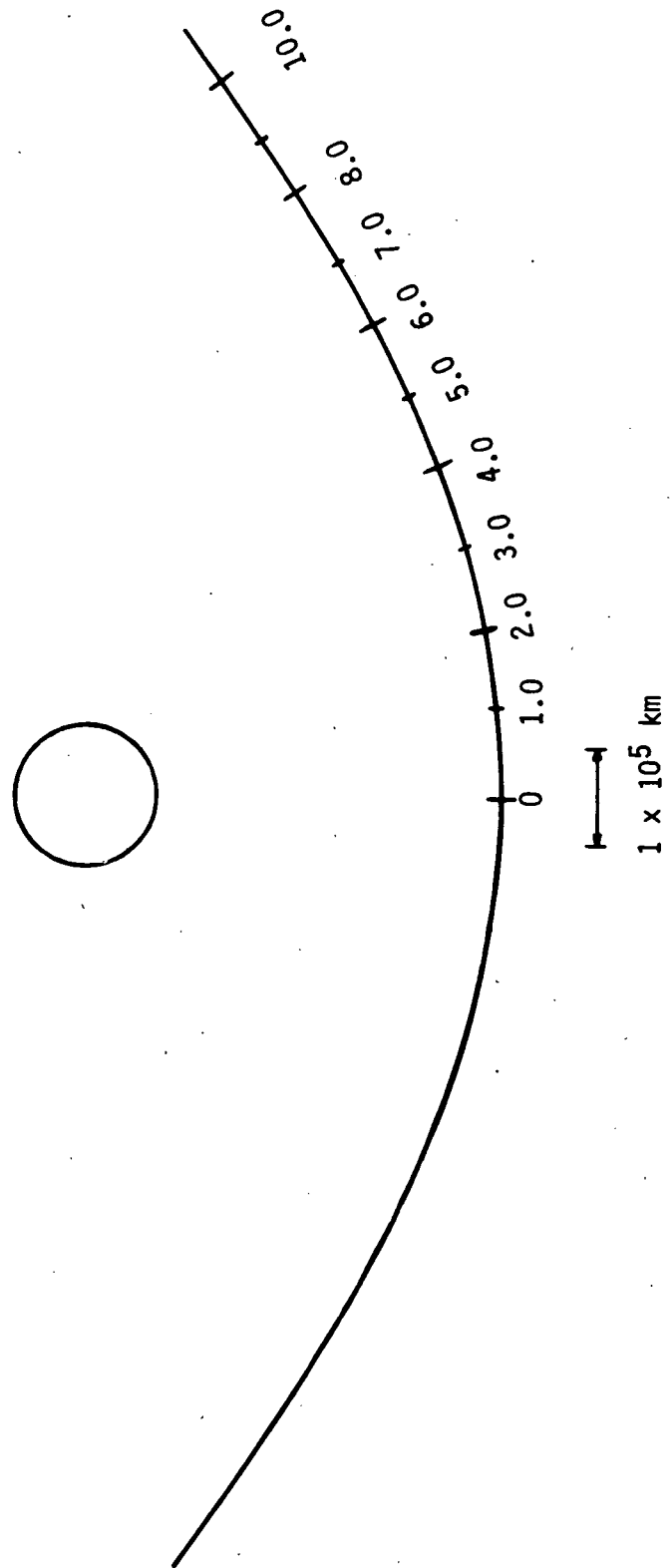


Figure B-5 Jupiter Flyby

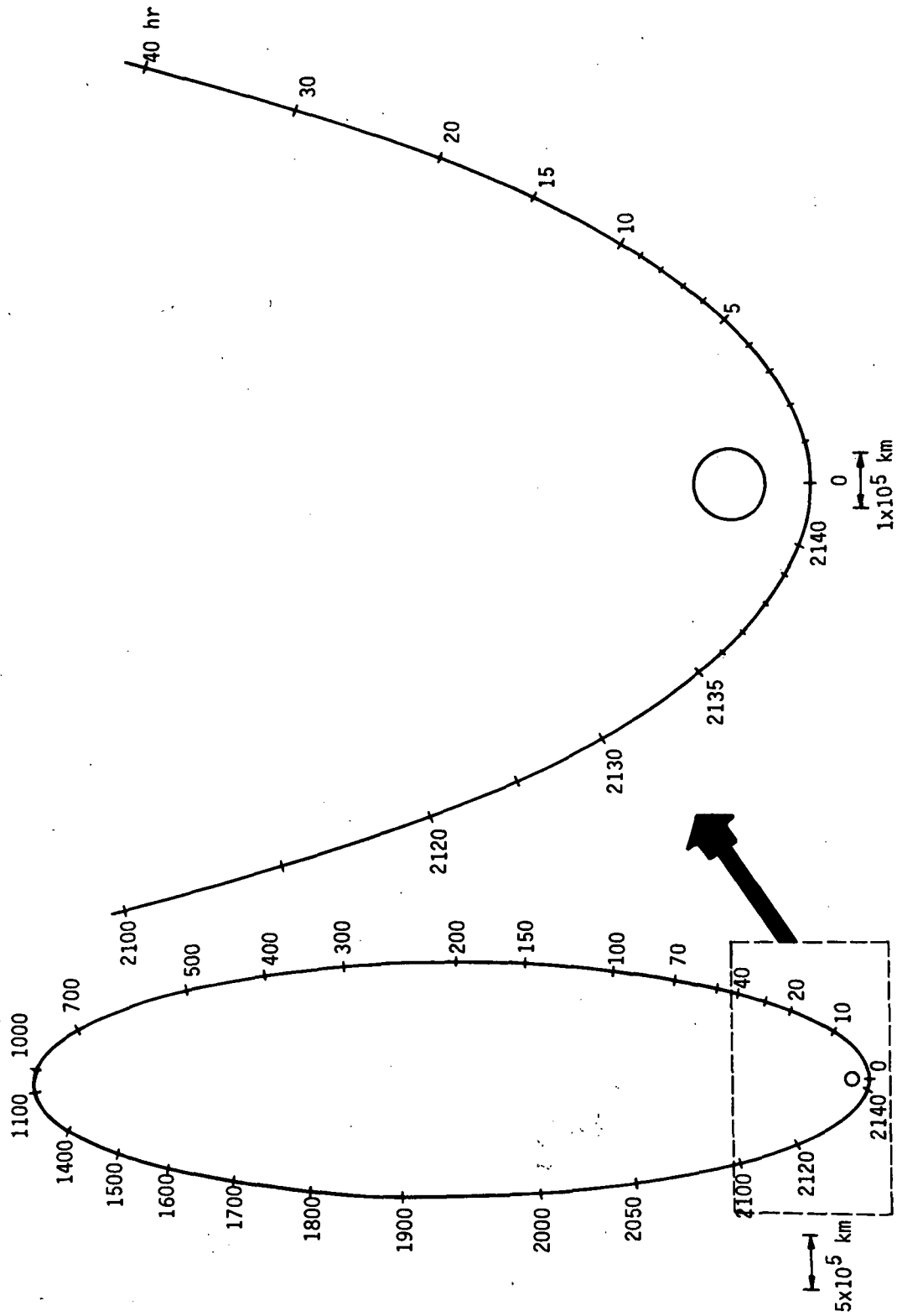


Figure B-6 Saturn Orbit

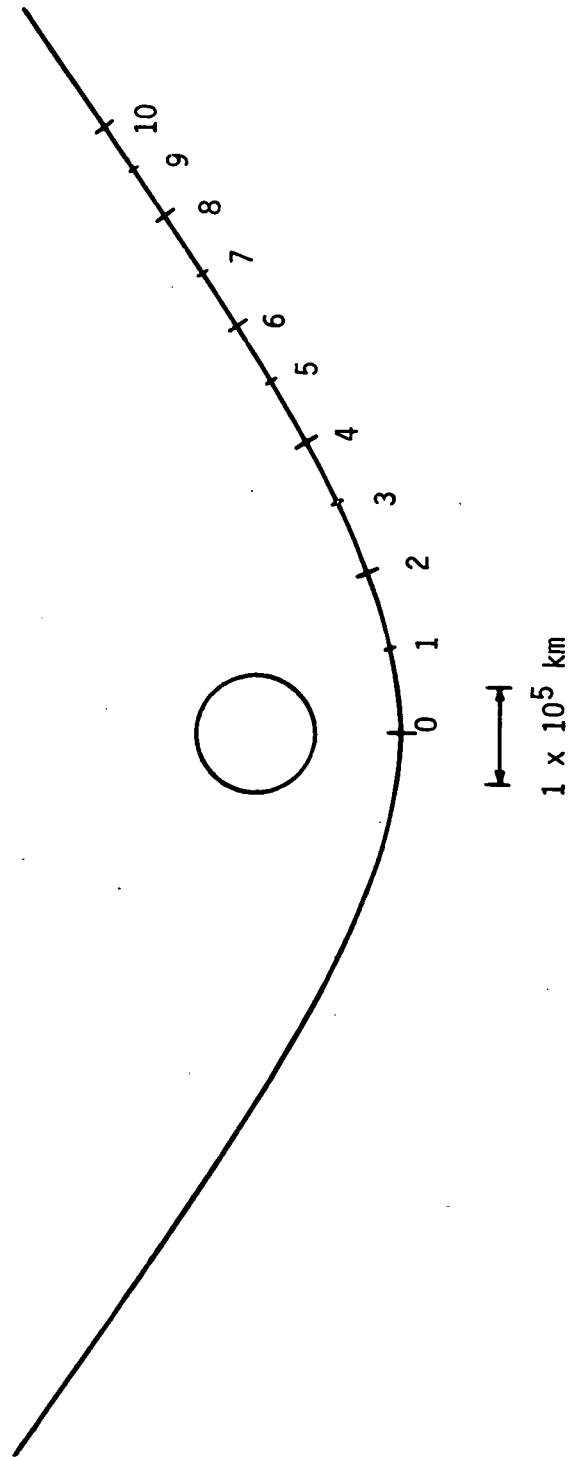


Figure B-7 Saturn Flyby

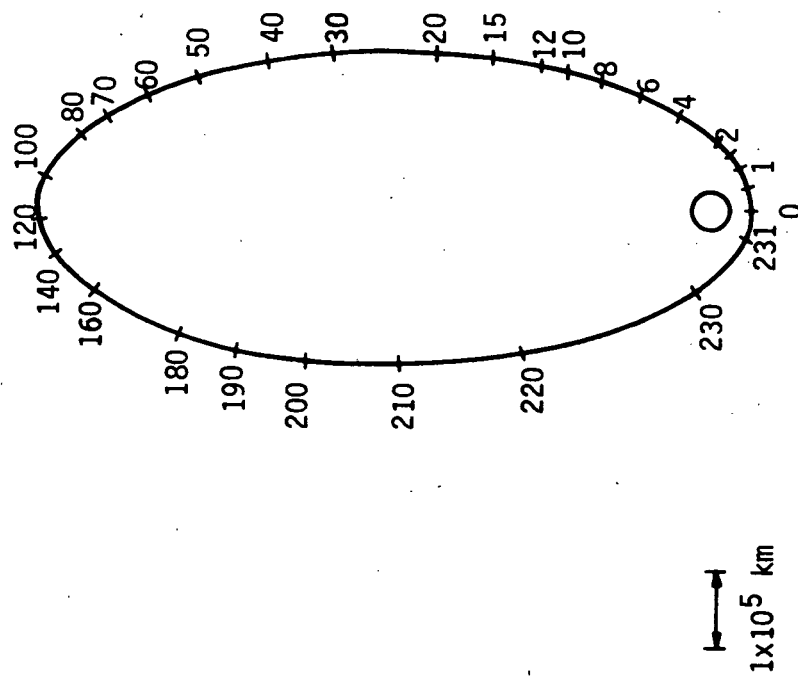


Figure B-8 Uranus Orbit

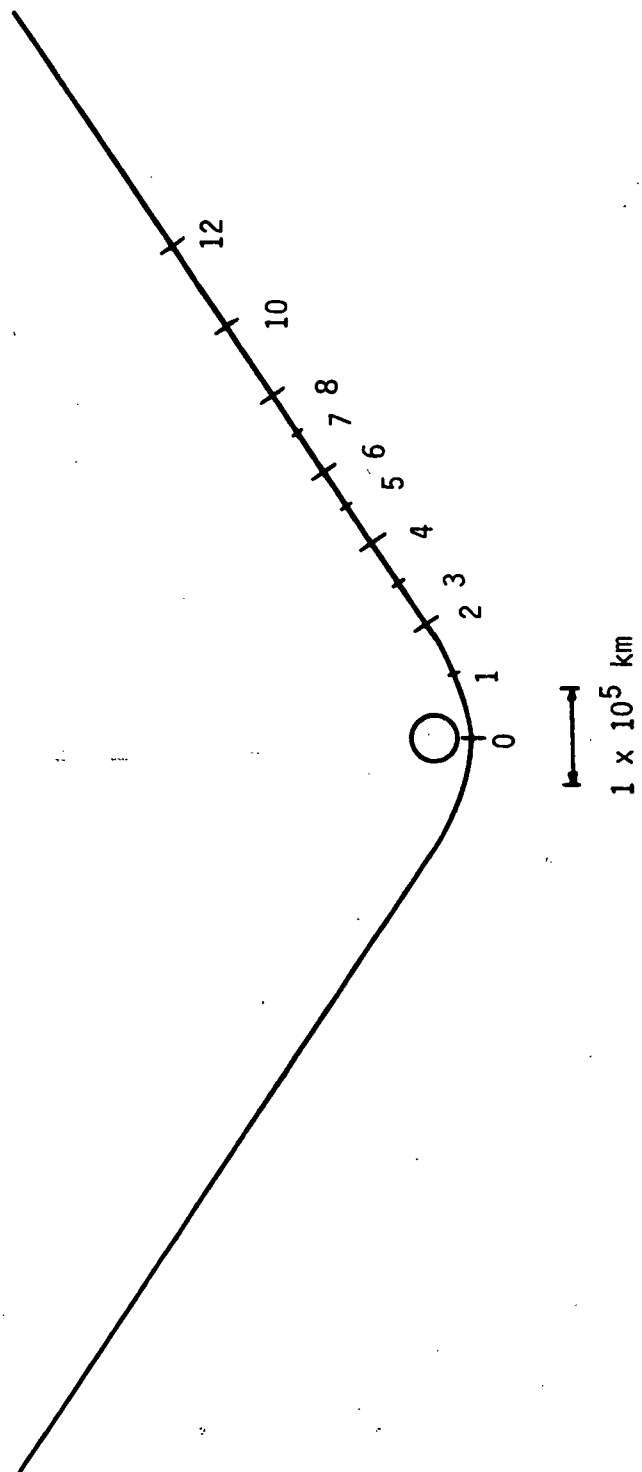


Figure B-9 Uranus Flyby

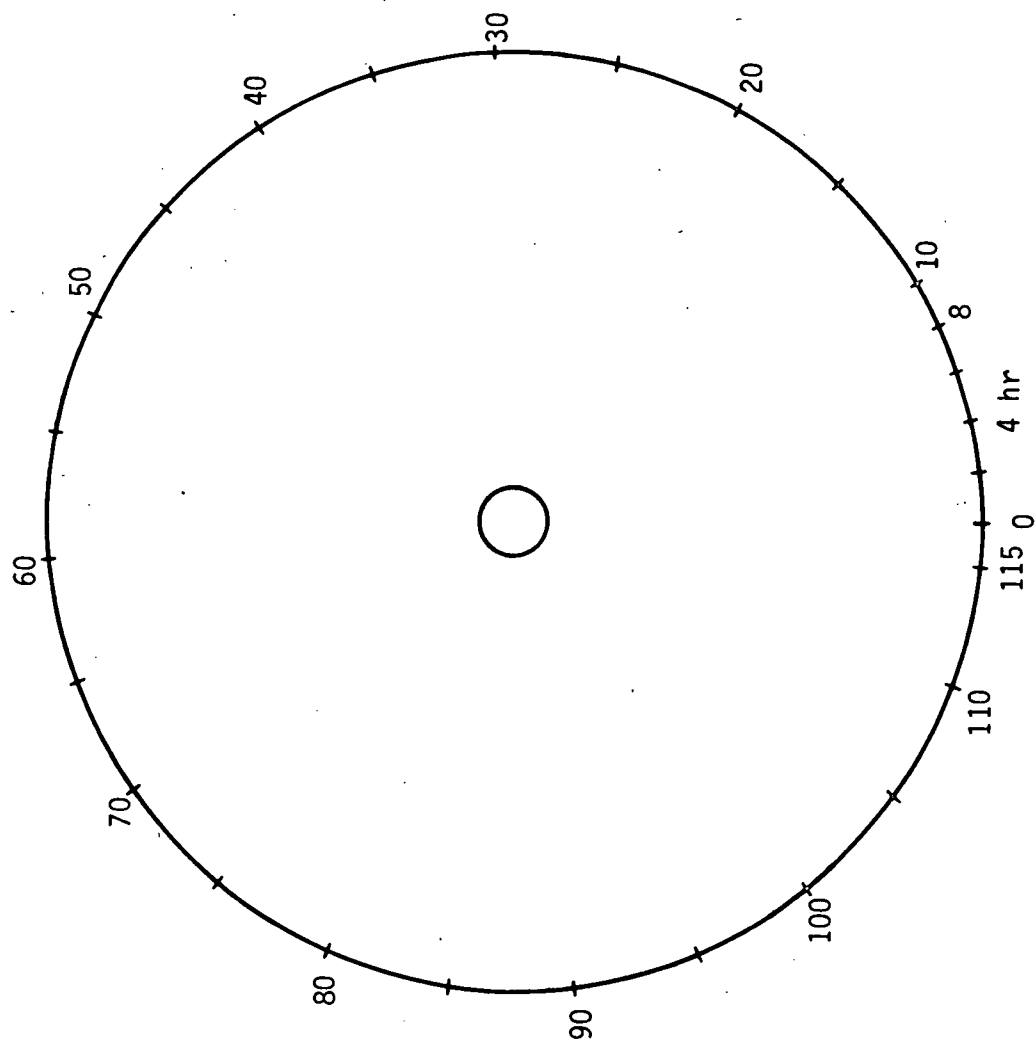


Figure B-10 Neptune Orbit

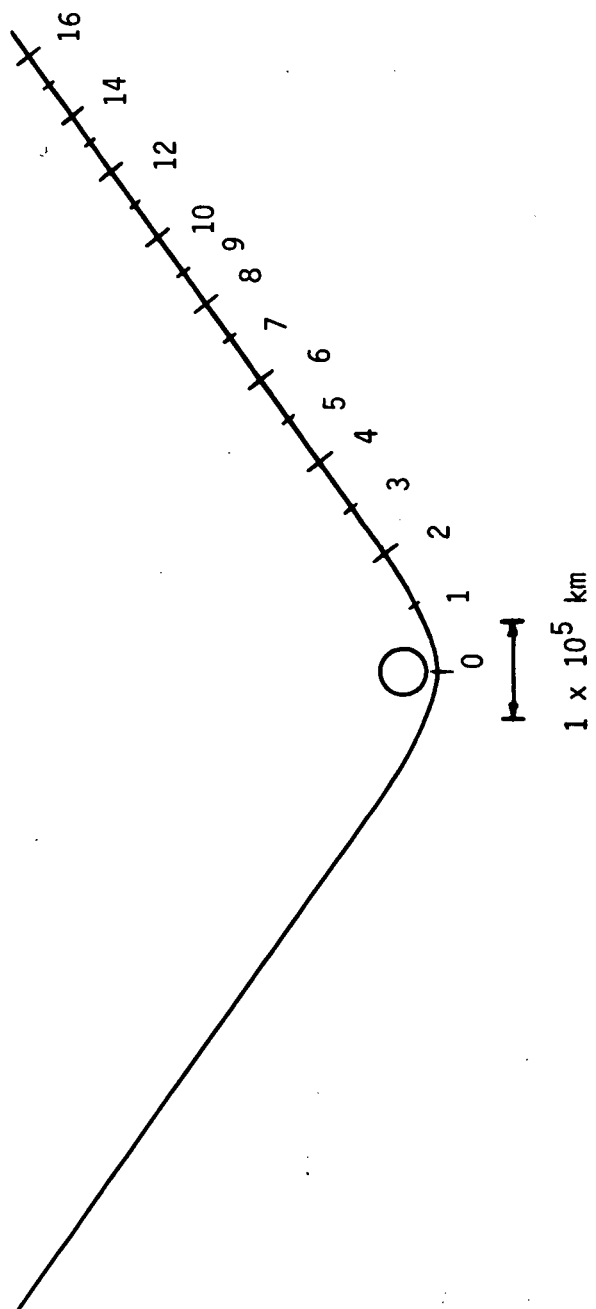


Figure B-11 Neptune Flyby

APPENDIX C

COMPUTER REQUIREMENTS SIZING ROUTINES

COMPUTER REQUIREMENTS SIZING ROUTINES

INTRODUCTION

In order to size the computer requirements for the large number of adaptive modes considered during the course of the contract, a modular approach was used. Using this method, a majority of the adaptive modes could be programmed using a relatively small number of modular routines.

The following information is given for the modular routines considered in this appendix:

1. Assumed list of required memory locations
2. A Fortran statement-level flow diagram
3. A listing of the specific instructions which would be required if the routine were to be used on the Viking GCSC computer.
4. An assembly language level flow diagram which plots in detail the transfer of data words within the computer as well as other specific programming instructions.

These modular routines fall into two general types: the first is concerned with the calculation of a value or a small number of values with a function. The second type provides the connective structure which employs modules of the first type, as well as reading in variables and outputting results. This sort of breakdown allows computations of various types to be used with a given structure. For example, the structure may read a stream of data, call for a computation, compare the results with an input standard and output a warning if the standard is exceeded. The computation itself can be varied to suit the occasion.

EVALUATION OF SIMPLE FUNCTION

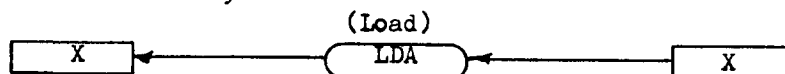
One-time evaluations of functions using simple operators can be done. The operators considered are: addition, subtraction, multiplication, division,

and the logical operators of AND, OR and exclusive OR. Any other operators such as exponential or trigonometric would require the use of a series.

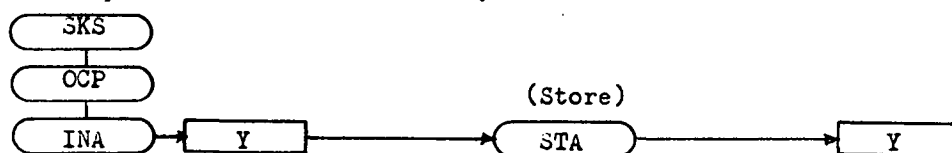
In the following discussion a simplified sizing of the evaluation of these simple functions is developed.

Input Types - Two types of inputs are possible.

1. Stored variables - These are variables which are loaded into memory locations by other routines or stored as a part of the original programming. In the discussion which follows the number of such variables is denoted by S.



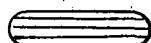
2. Input variables - These are variables for which the routine in question must test an input register for readiness, set up the register and then transfer the contents of the register into the Processor Unit's "A" register (a total of 3 words required). The number of such input variables is denoted by V.



In the following flow diagrams, instructions shown with an oval symbol, and memory locations or registers which are shown with a rectangular symbol are coded to indicate one of three possible functions performed.



Associated with transferring the variable into the proper register



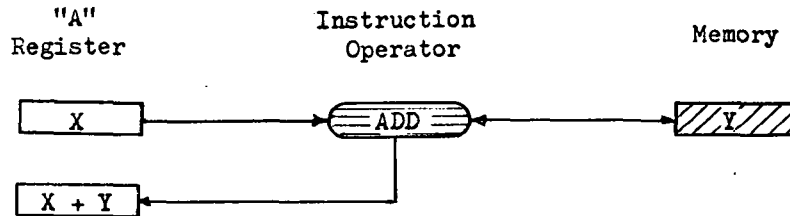
Operators



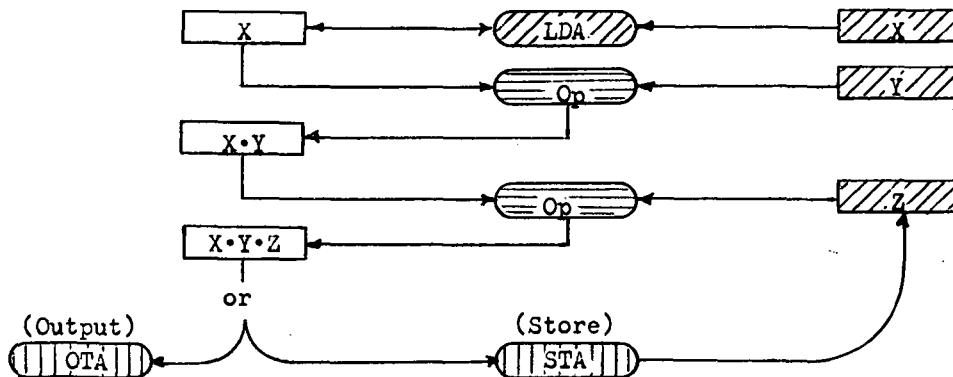
Associated with the output function

SIZING STANDARD BILATERAL OPERATIONS

Generally, the designated operator defines a bilateral mathematical operation to be performed between two operands, one held in the A and/or B registers and the other in a specified memory location. This may be diagrammed as below:



In order to perform two operations with three stored variables the following operations are required:

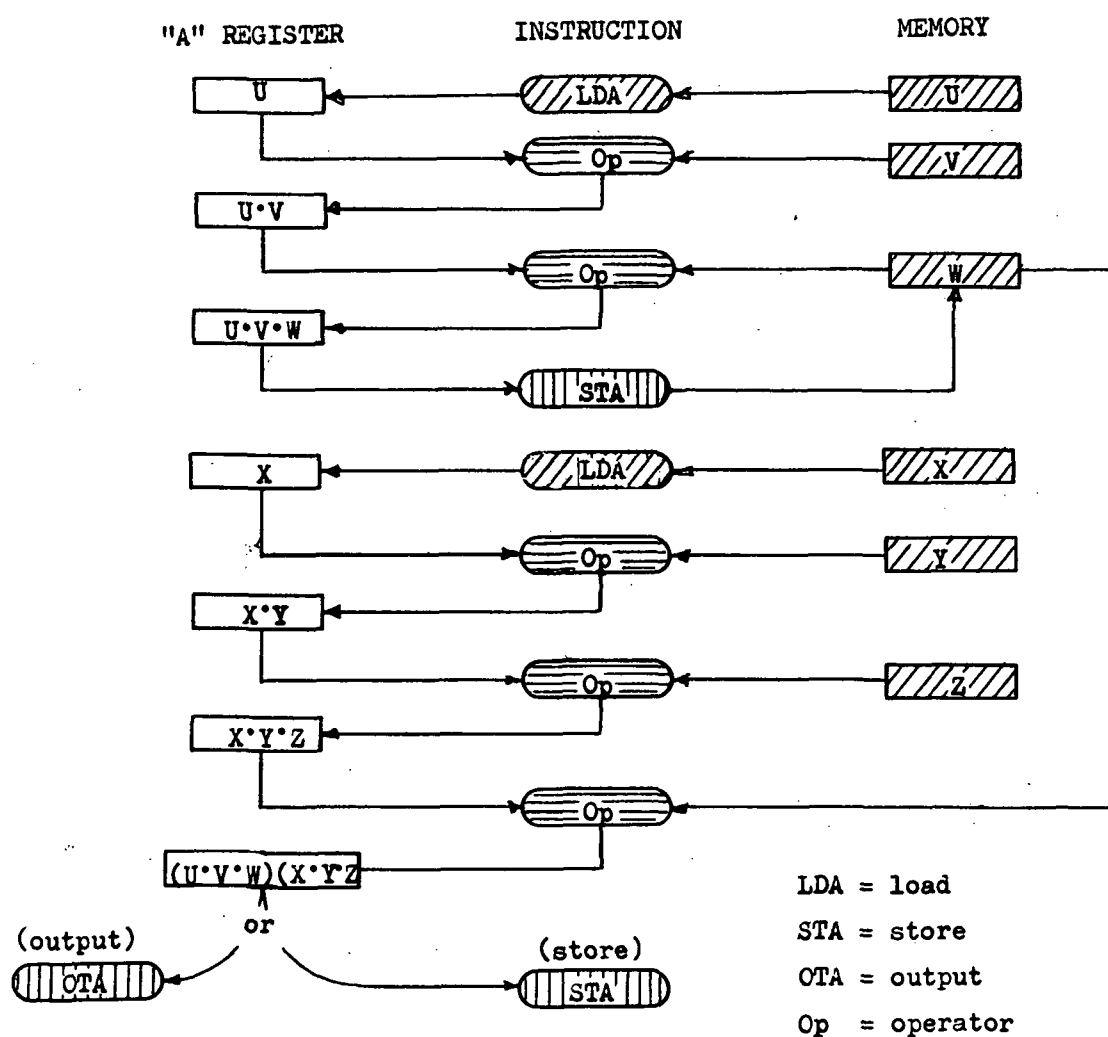


The number of words of memory required to effect this kind of evaluation which is confined to a single bracket (i.e. no storage of intermediate results is required) can be generalized as follows:

	Program	Memory	Total
S = No. of stored variables	1	S	S + 1
Op = No. of operators	Op	0	Op
Required for output	1	0	1

When more than a single bracket is required, an output function is needed for each bracket; one for the actual output and the others for storing the intermediate results.

Consider a function containing six variables, five operators grouped into two brackets, e.g., $(U \times V \times W) + (X \times Y \times Z)$ or $(U + V + W) / (X + Y + Z)$. The brackets may be functionally required as in the two examples or required because the intermediate results are desired for other purposes. An assembly language level flow diagram could look like this.



The only requirement for memory locations is to contain the stored variables providing that the intermediate result or the end result can be restored into previously used locations. The number of words required for B brackets can now be generalized.

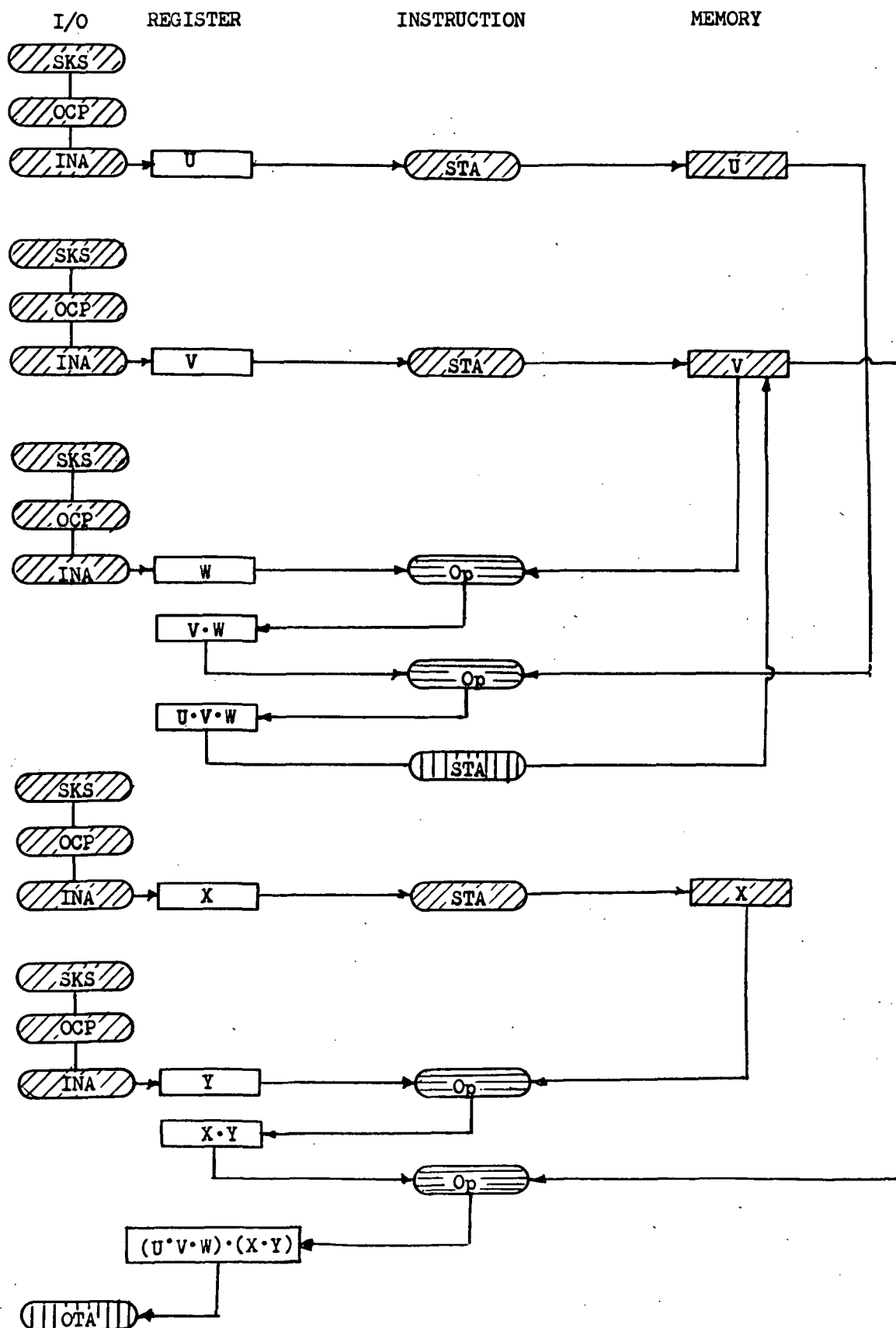
	Program	Memory	Total
S = No. of stored variables	B	S	S + B
Op = No. of operators	Op	O	Op
Required for output	B	O	B

In the example shown, where $Op=5$, $S=6$ and $B=2$, the memory required is:

$$\text{Total} = S + B + Op + B = 6 + 2 + 5 + 2 = 15$$

These 15 words are accounted for by nine instruction words and 6 memory location words.

A computation of similar complexity is shown below for input variables.



A fourth line can be added to the chart by a similar process to account for the effect of input variables. The number of such variables is denoted by V.

	Program	Memory	Total
V = No. of Input Variables	$4V-B$	$V-B$	$5V-2B$
S = No. of Stored Variables	B	S	$S + B$
Op = No. of Operators	Op	O	Op
Required for Output	B	O	B

In the example shown, where $V = 5$, $B = 2$, and $Op = 4$, the required memory is:

$$\text{Total} = (5V-2B) + Op + B = (5 \times 5 - 2 \times 2) + 4 + 2 = 27$$

It should be noted that the two terms $(5V-2B)$ and $(S+B)$ both equal zero when $V=0$ or $S=0$ respectively. In general, both input variables and stored variables are used in a given function, which permits alternate computational schemes. Therefore, only approximate sizing of computer requirements is possible. A useful approximation is formed by the algebraic addition of the four terms.

$$\text{Total} = (5V-2B) + (S+B) + Op + B = 5V + S + Op$$

Two examples of a function evaluated with 2 input variables, 3 stored variables and 4 operators is shown on the following pages. The approximate number of words required determined by the above relation is:

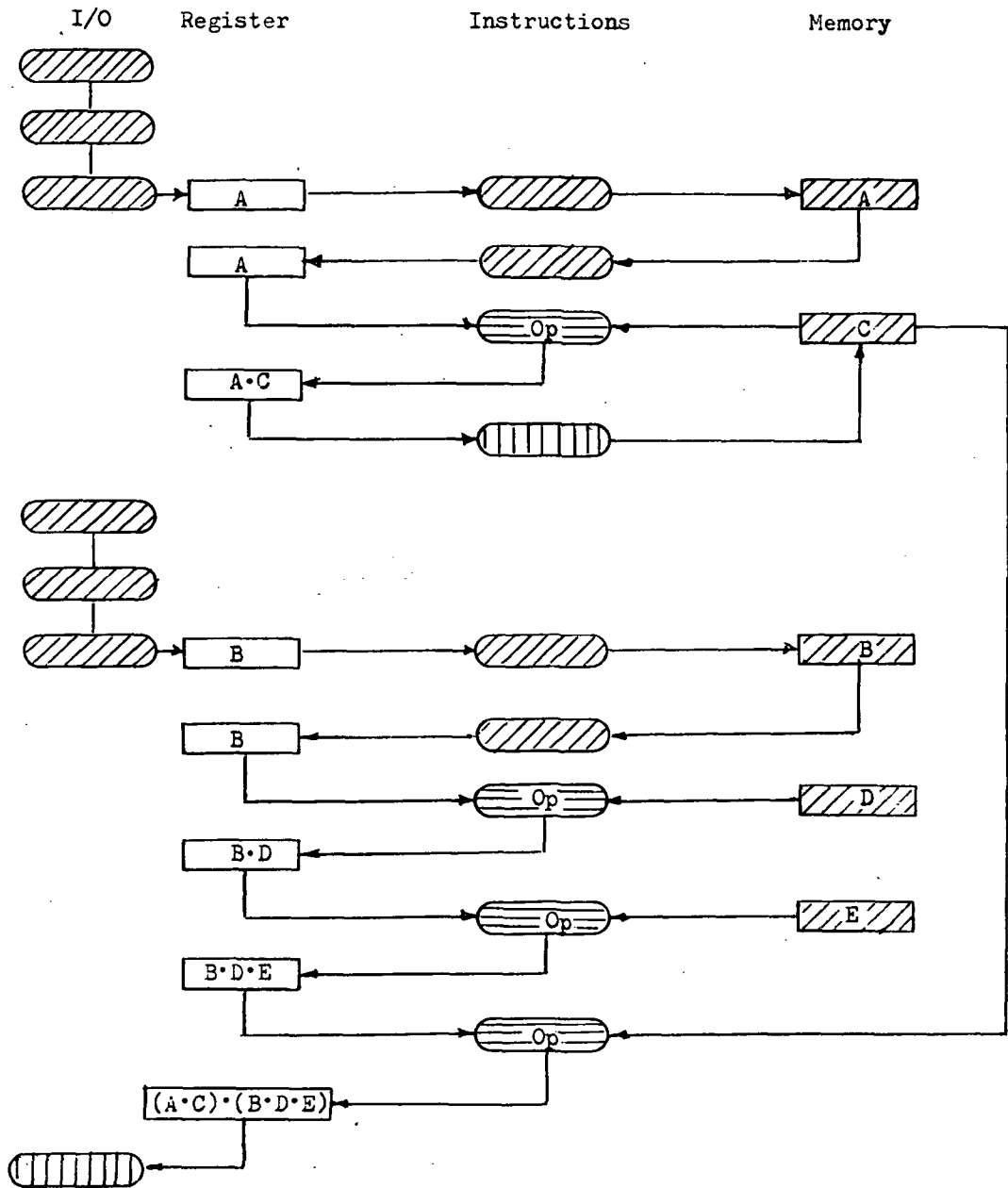
$$\text{Total} = 5 \times 2 + 3 + 4 = 17 \text{ words.}$$

FUNCTION $(A \cdot C) \cdot (B \cdot D \cdot E)$

C-9

A & B Input Variables

C, D & E Stored Variables



7 I/O

+

9 Instructions

+

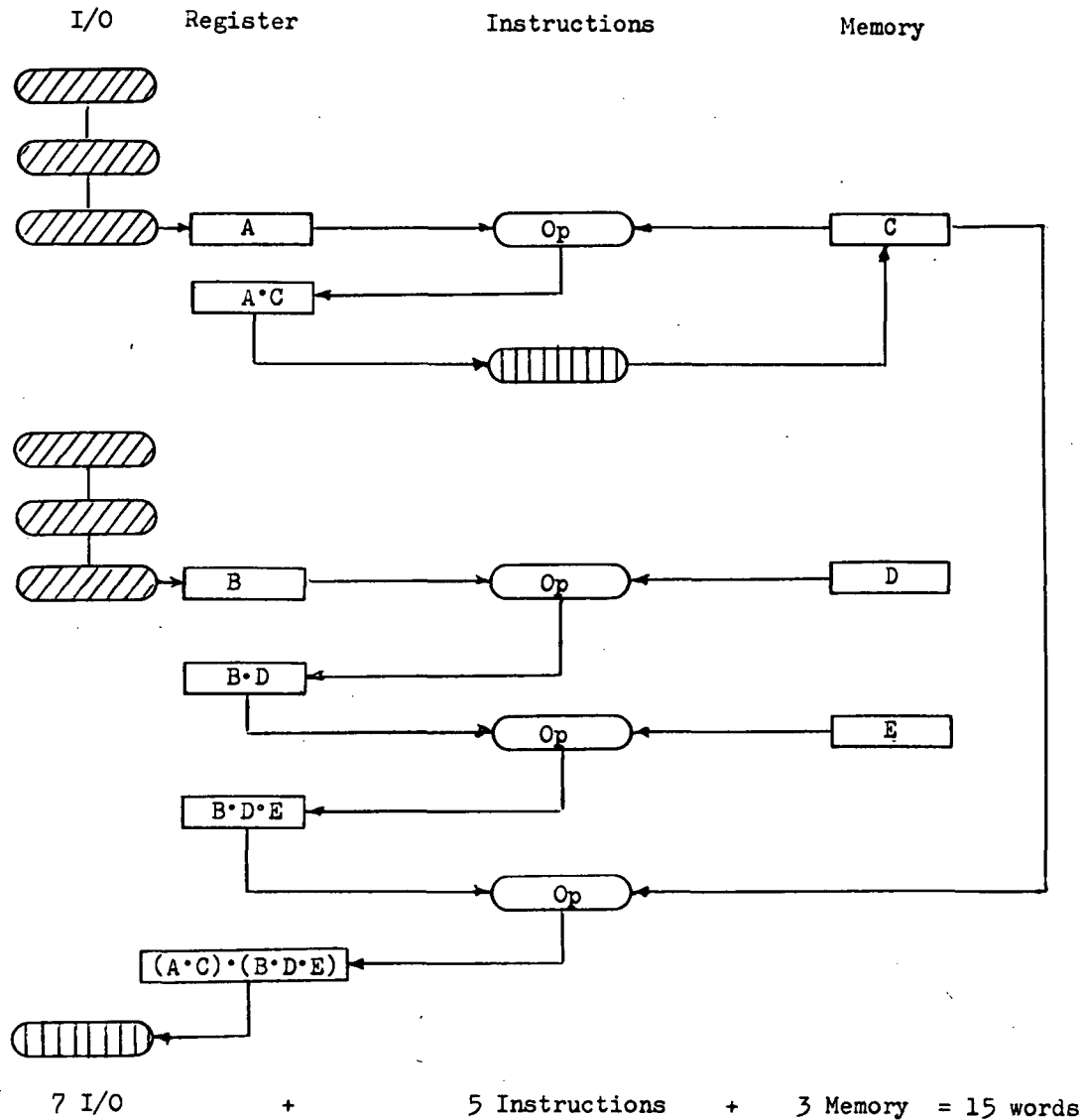
5 Memory = 21

(number of words approximated to be 17 words)

Function $(A \cdot C) \cdot (B \cdot D \cdot E)$

A & B Input Variables

C, D & E Stored Variables



(number of words approximated to be 17 words)

It can be seen that the approximate method of sizing memory requirements lies between two of the possible ways to program this function. An additional word of memory would be required if the value for C must be preserved, to hold the bracketed value for $A \cdot C$ while computing $(B \cdot D \cdot E)$.

Multiplication and Division

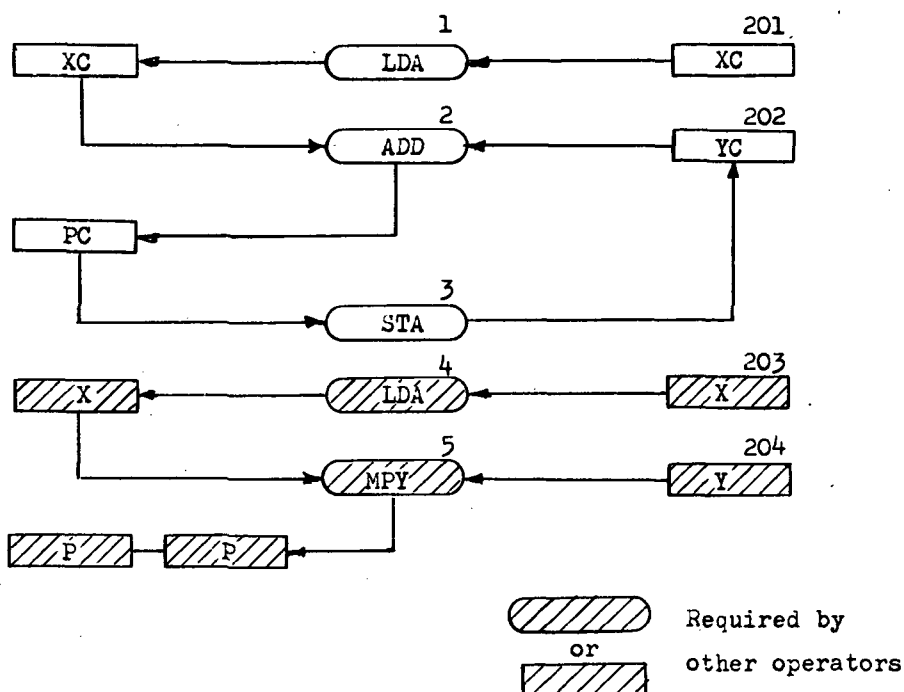
All but two of the possible operators require a single instruction to perform their function once the two variables concerned are loaded in their proper positions. Multiplication and division require extra words of programming or memory. In the GCSC computer, these operators are performed in a fractional mode, so that either a shift count of the value must be accounted for or a shift of the result must be made in the case of integer arithmetic. In integer multiplication, this one bit right shift requires an extra word of programming, while with floating point multiplication four extra words of programming and memory are required to keep track of the bit shift counts which must be added and stored.

In floating point division an extra ten words of programming and memory are required because of the necessary precaution of avoiding quotients which are greater than unity. This latter problem requires two shifts, one of the dividend and the other of the dividend count. In addition two words of memory are required to provide a double precision dividend required by the routine. Integer division requires only two words more than the ordinary operators. The single word needed in addition to multiplication is required to load zeros into the double precision format.

Assembly language level flow diagrams of the two types of multiplication and division are shown on the following pages.

-FLOATING POINT MULTIPLICATION-

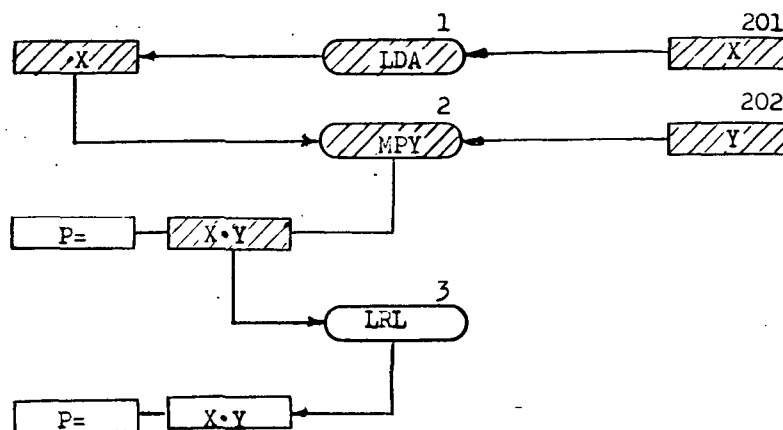
$$P = X \cdot Y$$



P	Instructions	Mnem	Description
00001	55 000 201	LDA	Load Xcount
00002	66 000 202	ADD	Add Ycount
00003	41 000 202	STA	Store product count
00004	55 000 203	LDA	Load Factor X
00005	64 000 204	MPY	Multiply by Factor Y

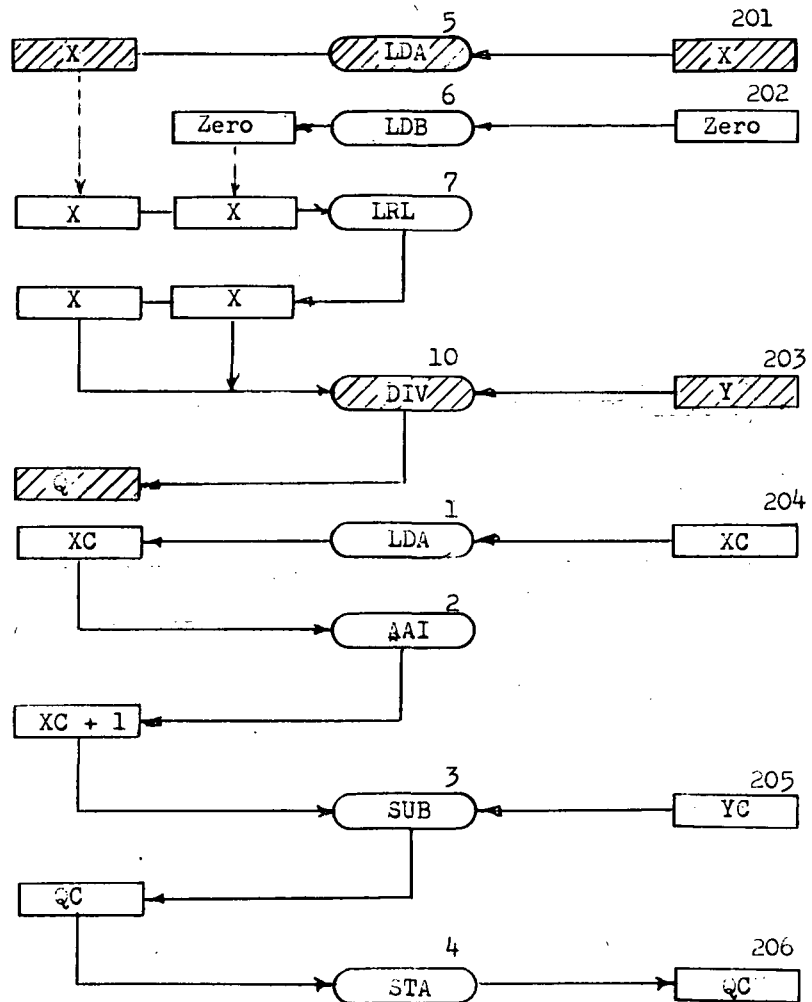
-this operation requires an additional 4 words-

-INTEGER MULTIPLICATION-

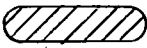


F	Instructions	Mnem	Description
00001	55 000 201	LDA	Load Factor X
00002	64 000 202	MPY	Multiply by Factor Y
00003	11 000 001	LRL	Long Right Shift 1 bit

-FLOATING POINT DIVISION-



$$Q = \frac{X}{Y}$$

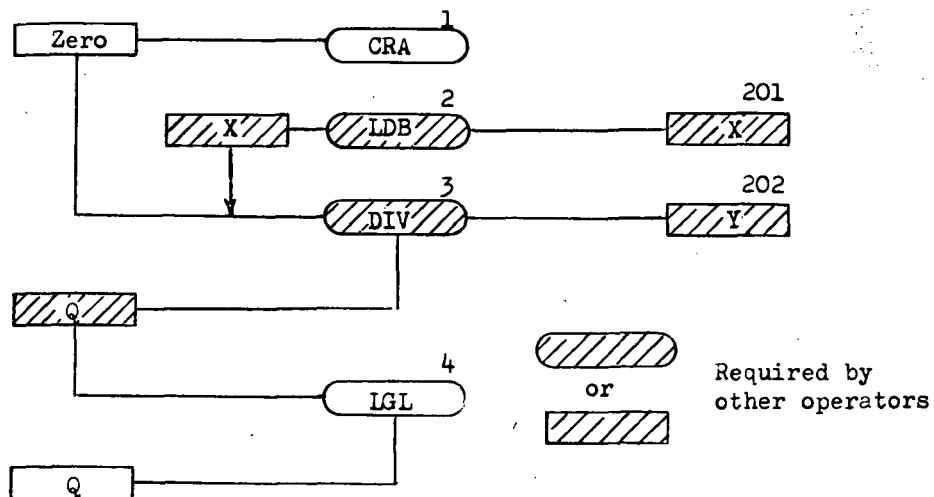
 Required for
or
 other operators

P	Instructions	Mnem	Description
00001	55 000 204	LDA	Load Xcount
00002	24 000 001	AAI	Add 1 to Xcount
00003	67 000 205	SUB	Subtract Ycount
00004	41 000 206	STA	Store Quotient Count
00005	55 000 201	LDA	Load X in "A" Register
00006	60 000 202	LDB	Load zero in "B" Register
00007	11 000 001	LRL	Long logical right shift
00010	65 000 203	DIV	Divide by Y

This operator requires 10 words more than the simple operator in order to provide a double precision dividend, to right shift result one bit and to keep track of shift counts.

-INTEGER DIVISION-

$$Q = \frac{X}{Y}$$



P	Instructions	Mnem	Description
00001	01 000 000	CRA	Clear "A" Register
00002	60 000 201	LDB	Load X into "B" Register
00003	65 000 202	DIV	Divide X by Y
00004	15 000 001	LGL	Logical Left Shift 1 bit

This operation requires two additional words more than other operators.

SIMPLE STATISTICAL COMPUTATIONS

Four simple statistical quantities have been found to be valuable in making decisions based on data trends. Although other relations could also be used, the simple relations described below do not require the storage of great amounts of data.

Mean of a set of data - A value of the mean is maintained by storing a summation of the values previously read in the set in question and the number of values. The quotient of this summation divided by the number n is the mean. This calculation routine requires five words of memory storage and eighteen words of programming, a total of 23 words. In order to stop the calculation a flag is set to unity which also resets the routine.

Variance of a set of data - In addition to the parameters stored for the calculation of the mean this routine also calculates and stores the summation of the squares of the values which form the set of data and the square of the mean. The summation of the squares of the values divided by the number of values is the second moment. When the square of the mean is subtracted from the second moment the difference is the second central moment or variance.

$$\text{Variance} = \frac{\sum v^2}{n} - (\text{mean})^2$$

This routine requires 10 words of memory and 32 words of programming. Again a flag is set to unity to terminate the calculation and reset the routine.

Running mean of a data stream - This routine performs the same calculation as the first described except that a constant number of points are considered; as a new value is added to the summation, another is subtracted having the value of the last mean. This routine requires seven words of memory and seventeen words of programming.

Running variance of a data stream - Similar to the running mean, this routine calculates the variance for a constant number of points, removing the oldest point when the newest value is added. This routine requires 10 words of memory plus one word for each point in the running sample and 49 words of programming.

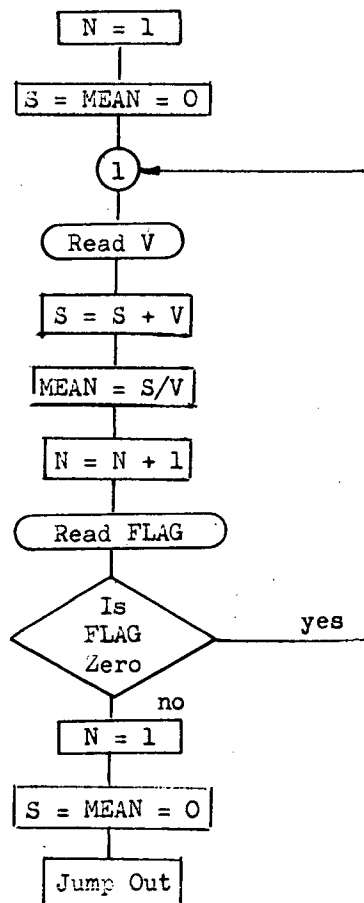
The following pages describe these routines in diagram fashion.

DETERMINE THE MEAN OF A SET
OF DATA

Memory Allocation

Location	Initial Value	Symbol	Description
00201	----	V	Stored value
00202	0000 0000	S	Summation of V
00203	0000 0001	N	Number of values in total set
00204	0000 0000	MEAN	Calculated mean
00205	0000 0000	FLAG	Stop flag set to 1 to stop routine

Flow Diagram



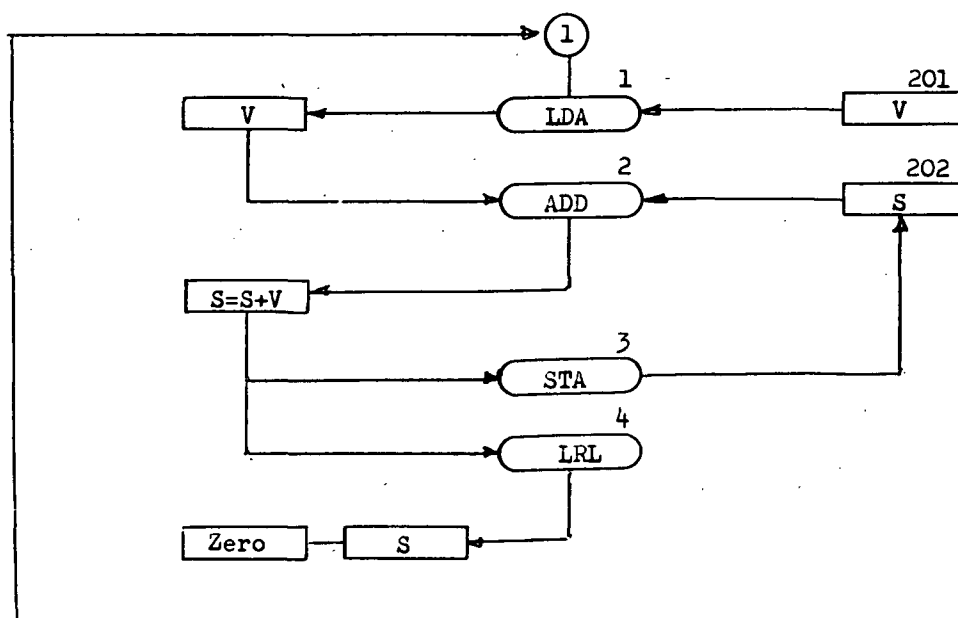
DETERMINE THE MEAN OF A SET

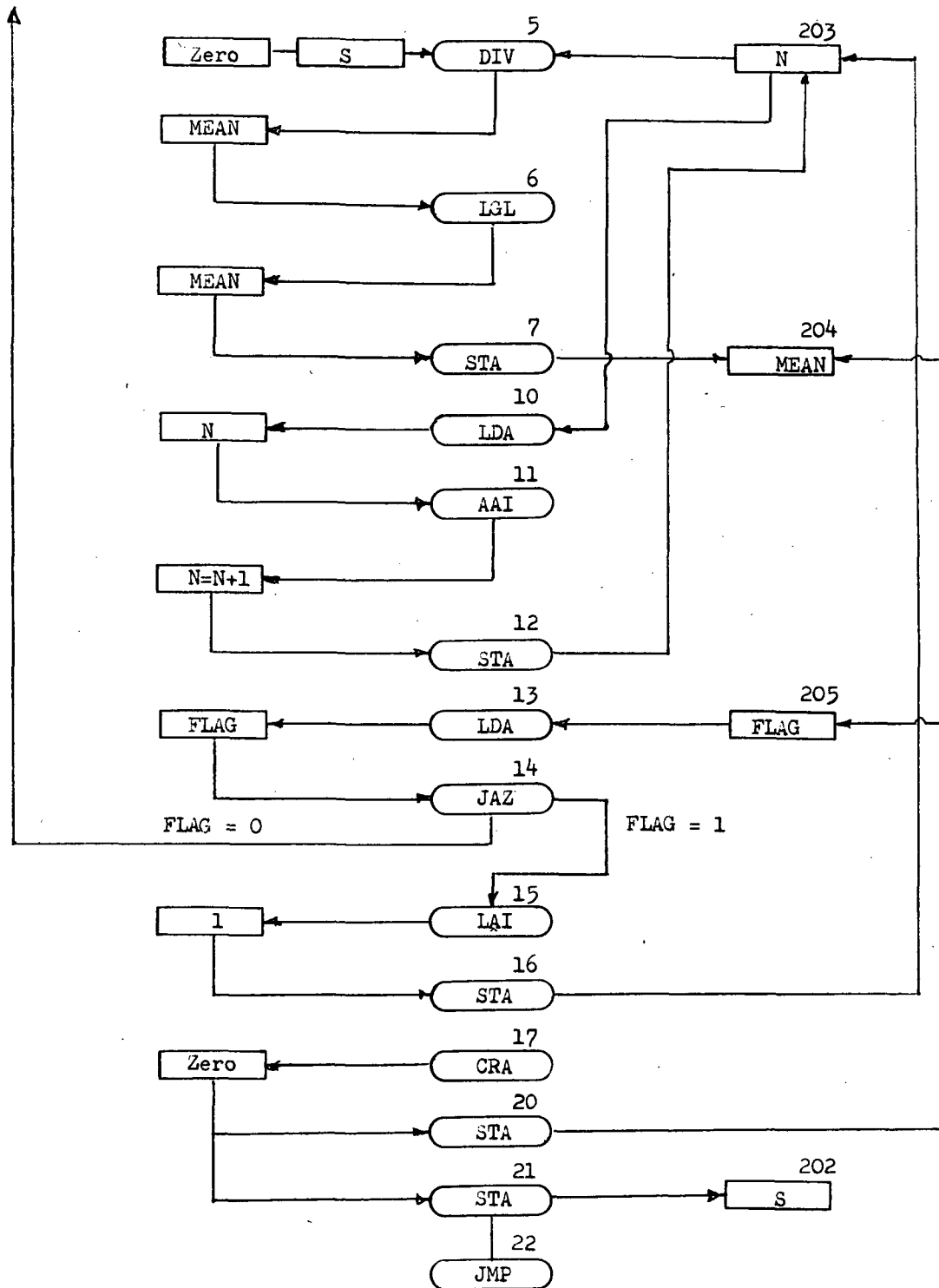
C-17

OF DATA

P	Instructions	Mnem	Description
00001	55 000 201	LDA	Load new value
00002	66 000 202	ADD	Add V to S
00003	41 000 202	STA	Store S
00004	11 000 030	LRL	Logical right shift 24 bits
00005	65 000 203	DIV	Divide S by N
00006	15 000 001	LRL	Logical left shift 1 bit
00007	41 000 204	STA	Store mean
00010	55 000 203	LDA	Load N into register
00011	24 000 001	AAI	Add 1 to N
00012	41 000 203	STA	Store N
00013	55 000 205	LDA	Load FLAG
00014	46 000 001	JAZ	Jump to 1 if FLAG is zero
00015	25 000 001	LAI	Load 1 into register
00016	41 000 203	STA	Store 1 into N
00017	01 000 000	CRA	Clear "A" register
00020	41 000 205	STA	Set FLAG = zero
00021	41 000 202	STA	Set S = zero
00022	44 000 xxx	JMP	Jump out of routine to xxx

Instruction Level Flow Diagram

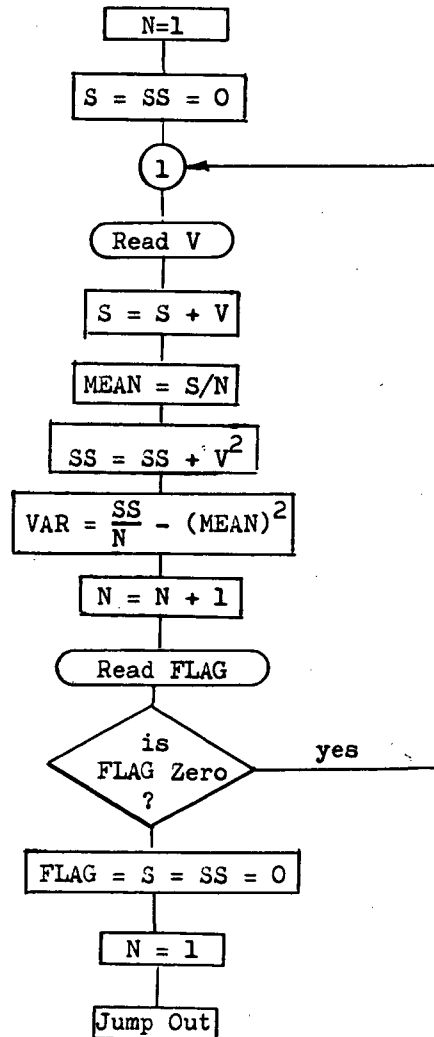




Memory Allocations

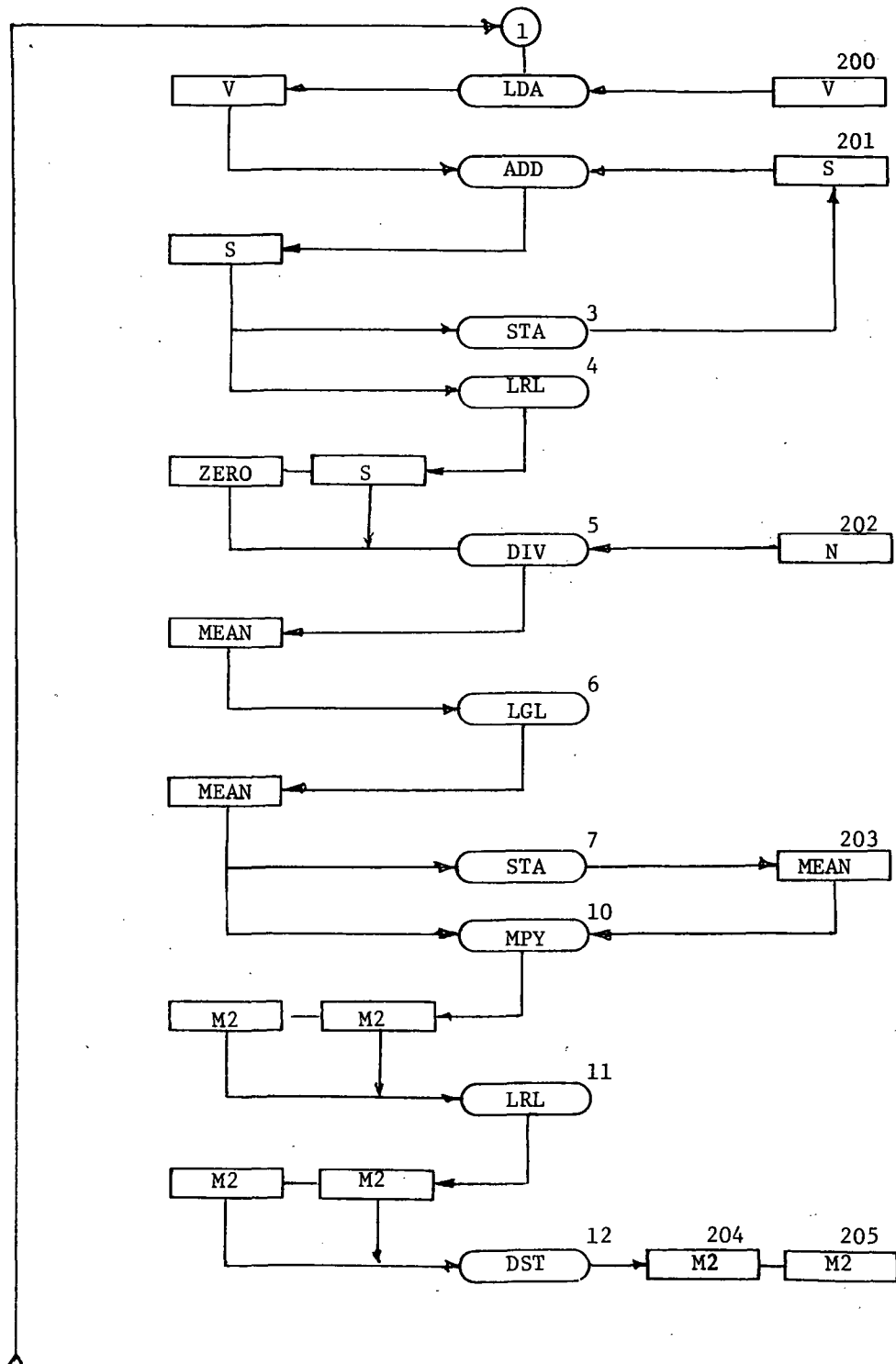
Location	Initial Value	Symbol	Description
00200	----	V	Stored value
00201	0000 0000	S	Summation of V
00202	0000 0001	N	Index number of V
00203	----	MEAN	Mean value
00204	----	M2	Square of the mean
00205	0000 0000	SS	Summation of the squares of V
00207	0000 0000		
00210	----	VAR	Variance of dat set
00211	0000 0000	FLAG	Stop flag set to 1 to end routine

Flow Diagram

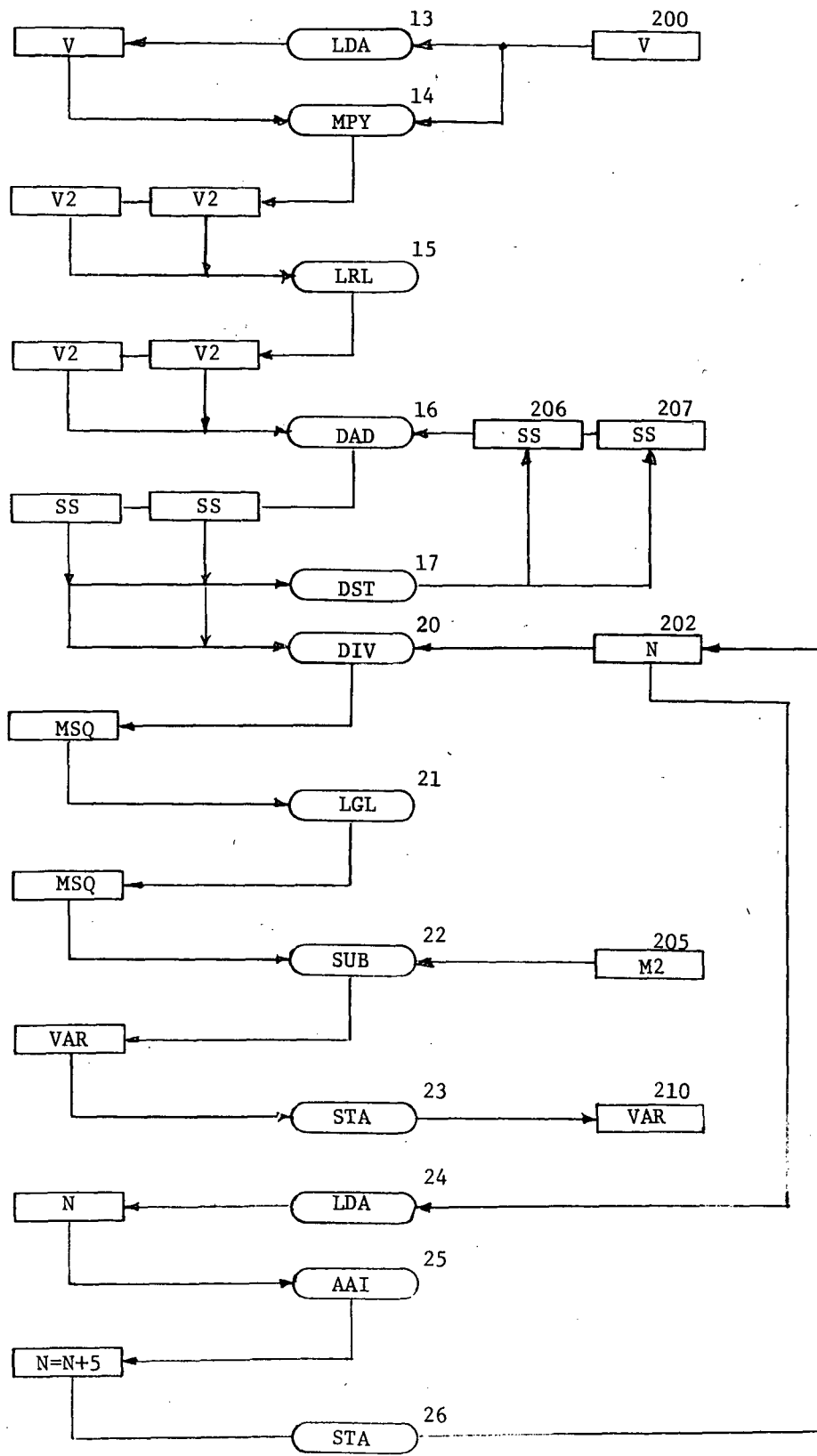


DETERMINE THE VARIANCE OF A SET OF DATA

P	Instructions	Mnem	Description
00001	55 000 200	LDA	Load value into register
00002	66 000 201	ADD	Add summation S to V
00003	41 000 201	STA	Store S in memory
00004	11 000 030	LRL	Shift S into B register
00005	65 000 202	DIV	Divide S by N
00006	15 000 001	LGL	Shift left 1 bit
00007	41 000 203	STA	Store MEAN in memory
00010	64 000 203	MPY	Square the Mean (M2)
00011	11 000 001	LRL	Right shift 1 bit
00012	74 000 204	DST	Store (double precision) M2
00013	55 000 200	LDA	Load V into register
00014	64 000 200	MPY	Square V (V^2)
00015	11 000 001	LRL	Right shift 1 bit
00016	76 000 206	DAD	Add (double precision) V^2 to SS
00017	74 000 206	DST	Store SS (double precision)
00020	65 000 202	DIV	Divide SS by N (MSQ)
00021	15 000 001	LGL	Left shift 1 bit
00022	67 000 205	SUB	Subtract M2 from MSQ (VAR)
00023	41 000 210	STA	Store Variance
00024	55 000 202	LDA	Load N into register
00025	24 000 001	AAI	Add 1 to N
00026	41 000 202	STA	Store augmented N
00027	55 000 211	LDA	Load FLAG into register
00030	46 000 001	JAZ	Jump to 1 if FLAG = 0
00031	01 000 000	CRA	Clear "A" register
00032	41 000 211	STA	Set FLAG = 0
00033	41 000 201	STA	Set S = 0
00034	41 000 206	STA	Set SS = 0
00035	41 000 207	STA	
00036	25 000 001	LAI	Load 1 into register
00037	41 000 202	STA	Set N = 1
00040	44 0xx xxx	JMP	Jump out of routine

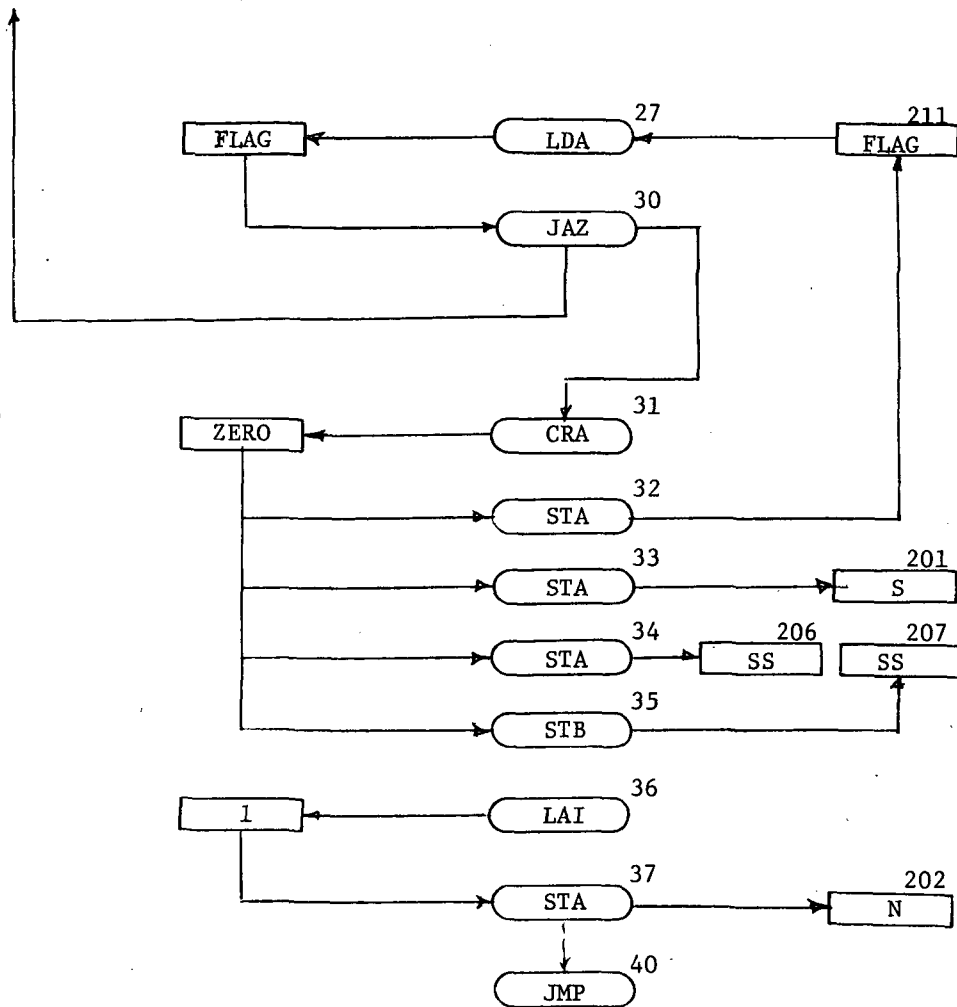


DETERMINE THE VARIANCE OF A SET OF DATA



DETERMINE THE VARIANCE OF A SET OF DATA

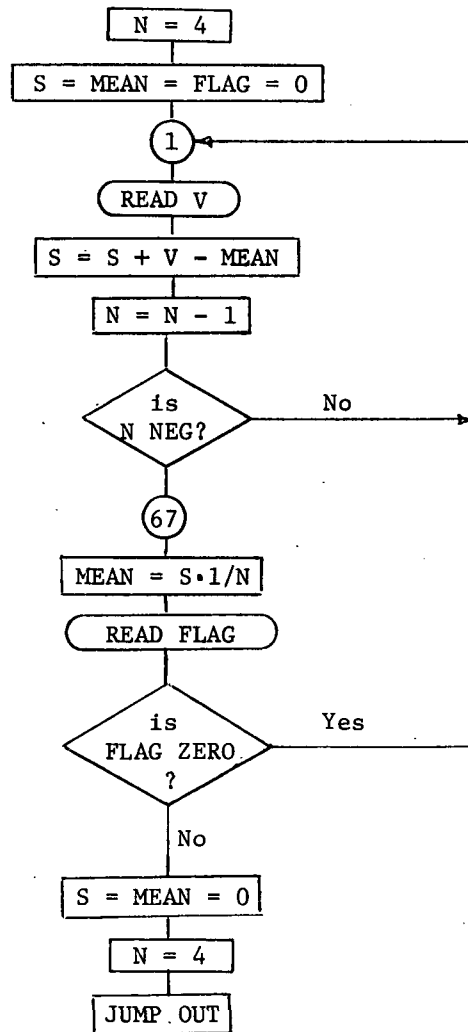
C-23



DETERMINE RUNNING MEAN

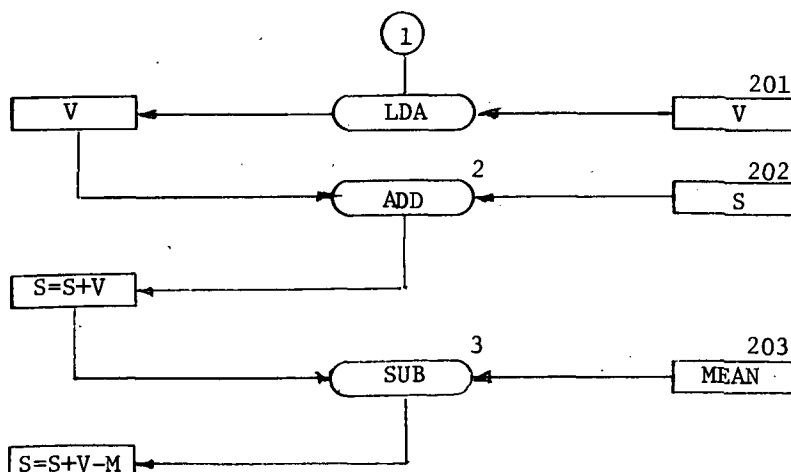
Memory Allocations

Location	Initial Value	Symbol	Description
00201	----	V	Input value
00202	0000 0000	S	Running sum
00203	0000 0000	MEAN	Running average
00204	7700 0004	N	Index of value
00205	0631 4632	$\frac{1}{N} (= \frac{1}{5})$	Reciprocal of no. of points
00206	0000 0000	FLAG	FLAG (set to 1 to stop)
00207	7700 0004	N	Reset value for N

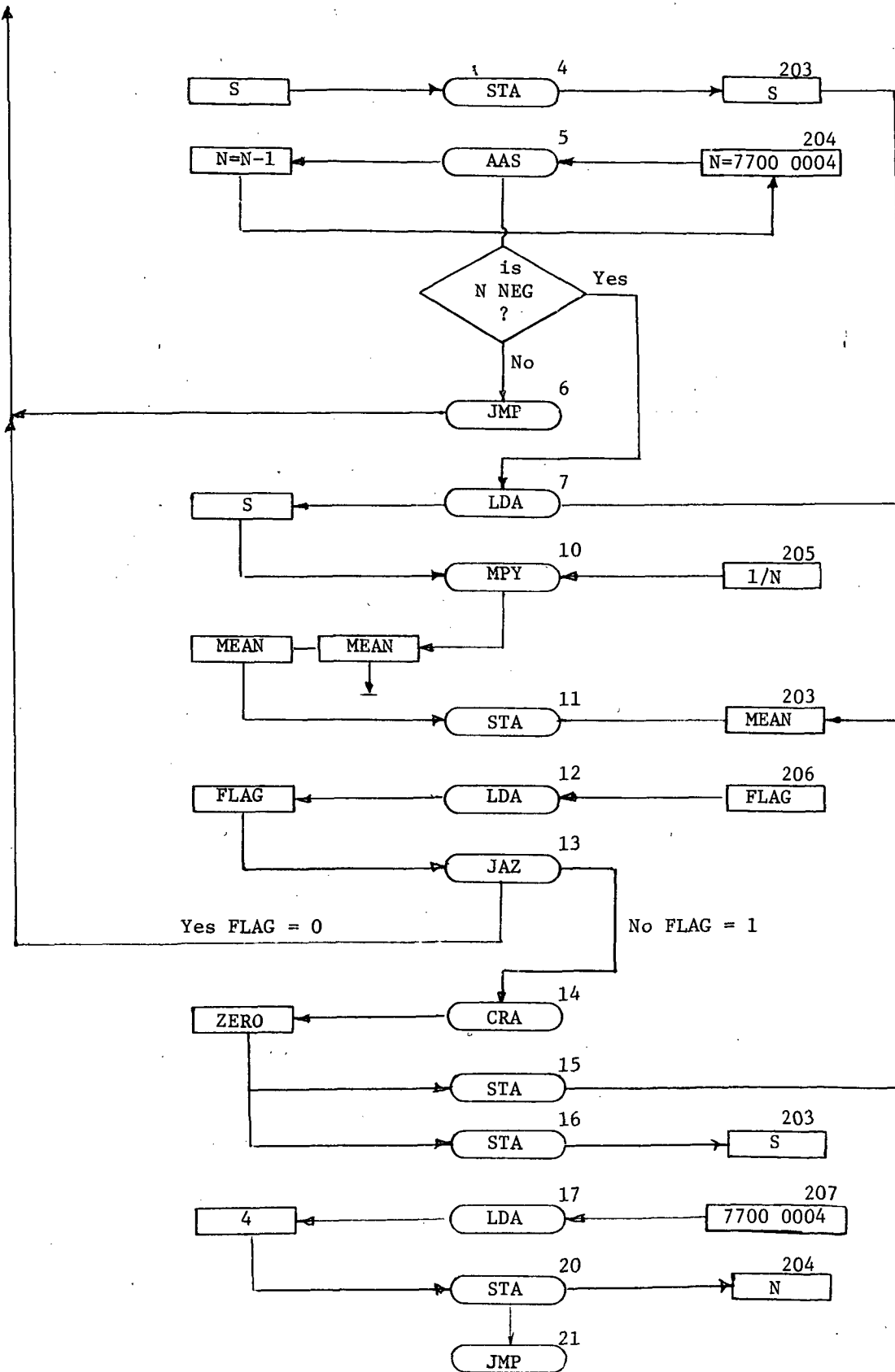


DETERMINE RUNNING MEAN

P	Instruction	MNEM	Description
00001	55 000 201	LDA	Loan new V into register
00002	66 000 202	ADD	Add S
00003	67 000 203	SUB	Subtract MEAN
00004	41 000 202	STA	Store $S = S + V - \text{MEAN}$
00005	72 000 204	AAS	Augment N and skip if NEG
00006	44 000 001	JMP	Jump to 1
00007	55 000 202	LDA	Load S into register
00010	64 000 205	MPY	Multiply by 1/N
00011	41 000 203	STA	Store $\text{MEAN} = S \cdot 1/N$
00012	55 000 206	LDA	Load FLAG
00013	46 000 001	JAZ	Jump to 1 if negative
00014	01 000 000	CRA	Clear "A" register
00015	41 000 203	STA	Set MEAN to zero
00016	41 000 202	STA	Set S to zero
00017	55 000 207	LDA	Load 7700 0004
00020	41 000 204	STA	Store reset N
00021	44 000 xxx	JMP	Jump out of routine



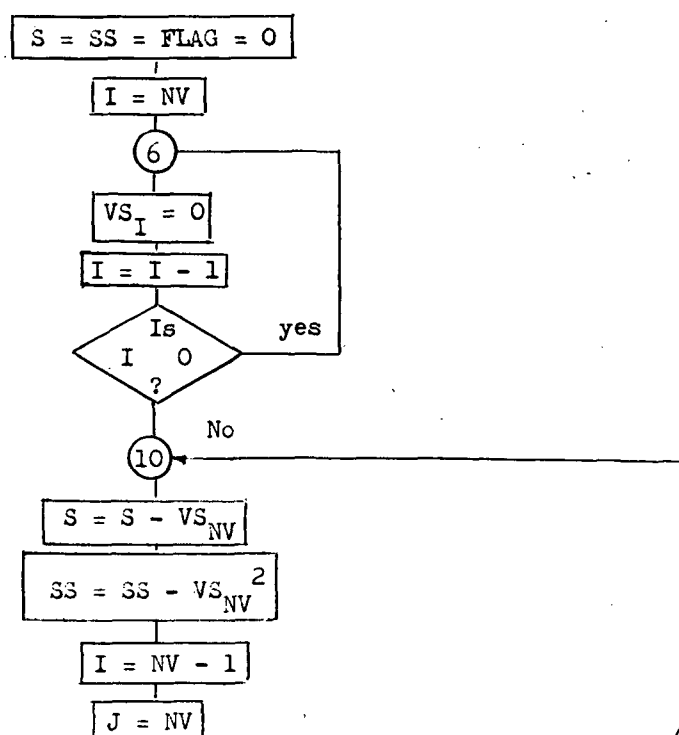
DETERMINE RUNNING MEAN



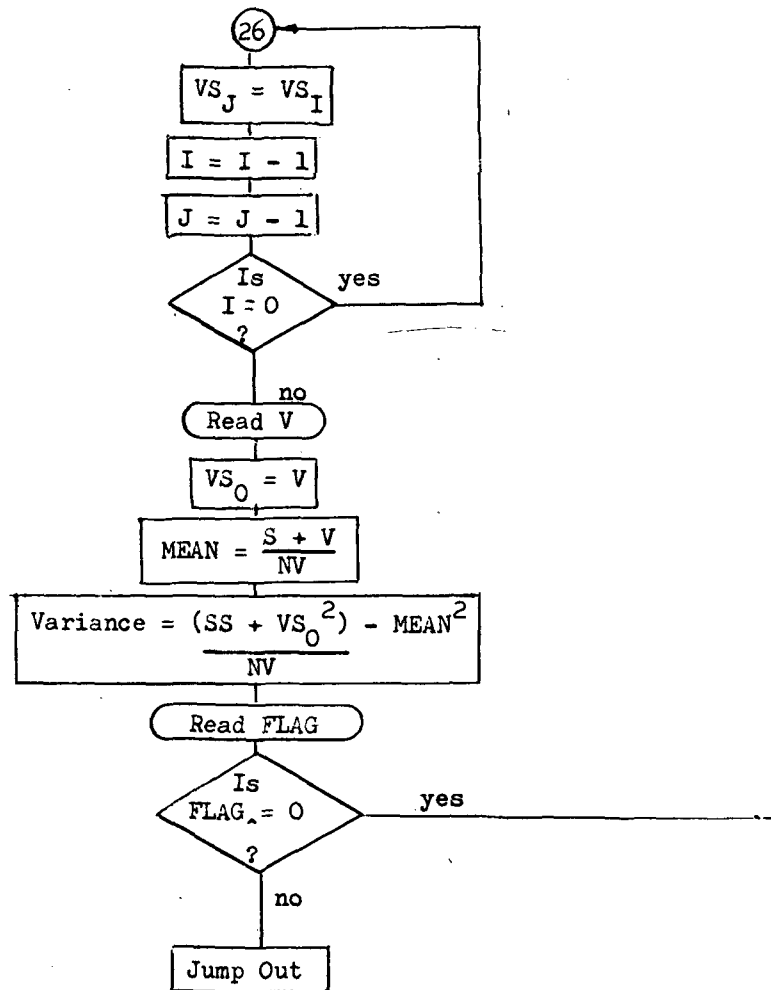
DETERMINATION OF RUNNING VARIANCE

MEMORY ALLOCATIONS

Location	Initial Value	Symbol	Description
00201	----	NV	Number of points in running sample
00202	0000 0000	S	Sum of NV values
00203	0000 0000	SS	Sum of values squared
00204	0000 0000	FLAG	Set to 1 to stop
00205	----	V	Input value
00206	----	VS_{NV}^2	Square of input value
00207	----	MEAN	Mean of N values
00210	----	M2	Square of mean
00211	----	VAR	Variance
00212	----	VS_0	} Stored value
00213	----	VS_1	
.	.	.	
.	.	.	
212+N	.	VS_N	



DETERMINATION OF RUNNING VARIANCE

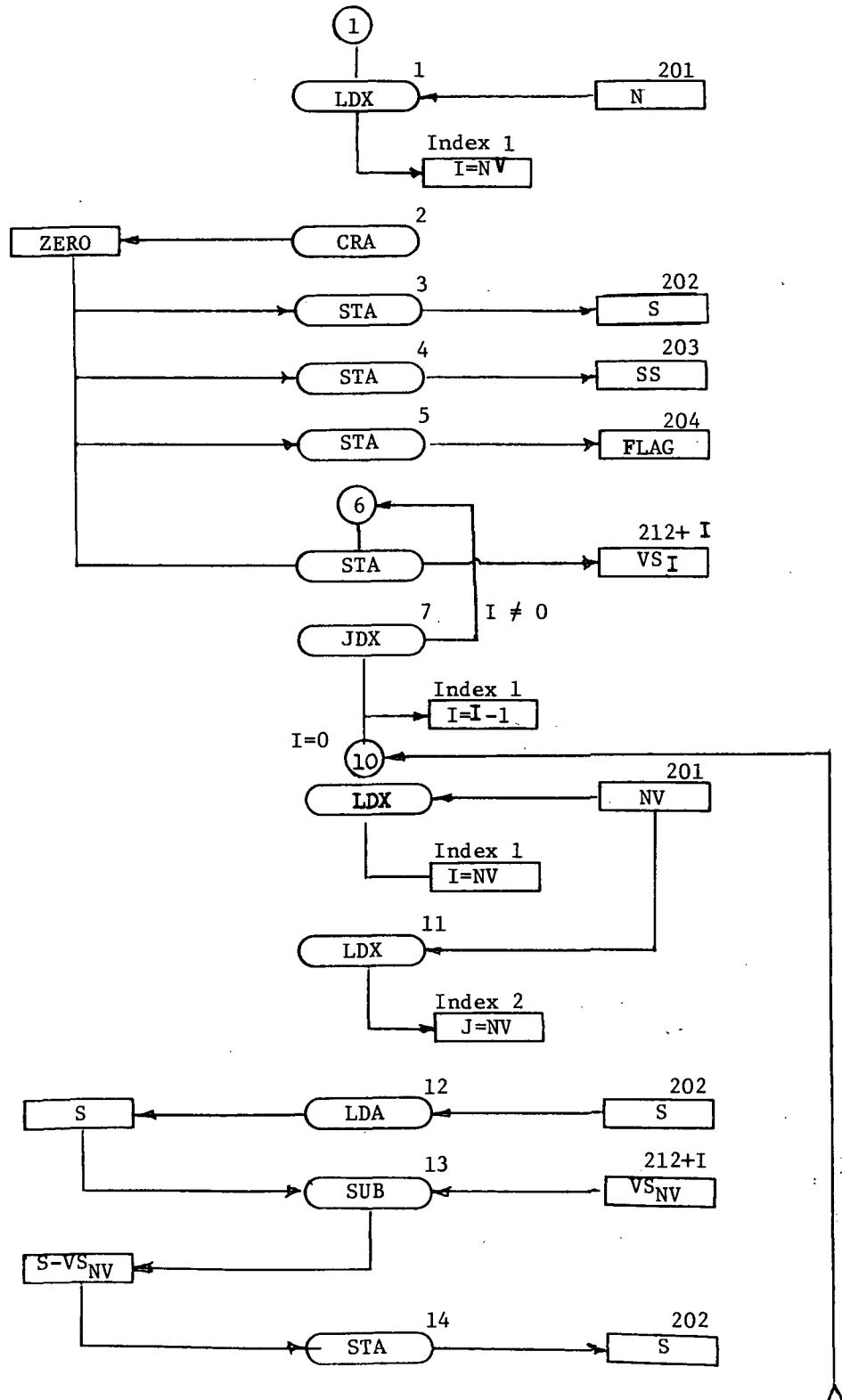


P	Instruction	MNEM	Description
00001	73 200 201	LDX	Set index 1 = NV
00002	01 000 000	CRA	Load zero into register
00003	41 000 202	STA	Set S = 0
00004	41 000 203	STA	Set SS = 0
00005	41 000 204	STA	Set FLAG = 0
00006	41 200 212	STA	Set $VS_j = 0$ (but not VS_0)
00007	71 200 006	JDX	Jump to 6 if Index $\neq 0$

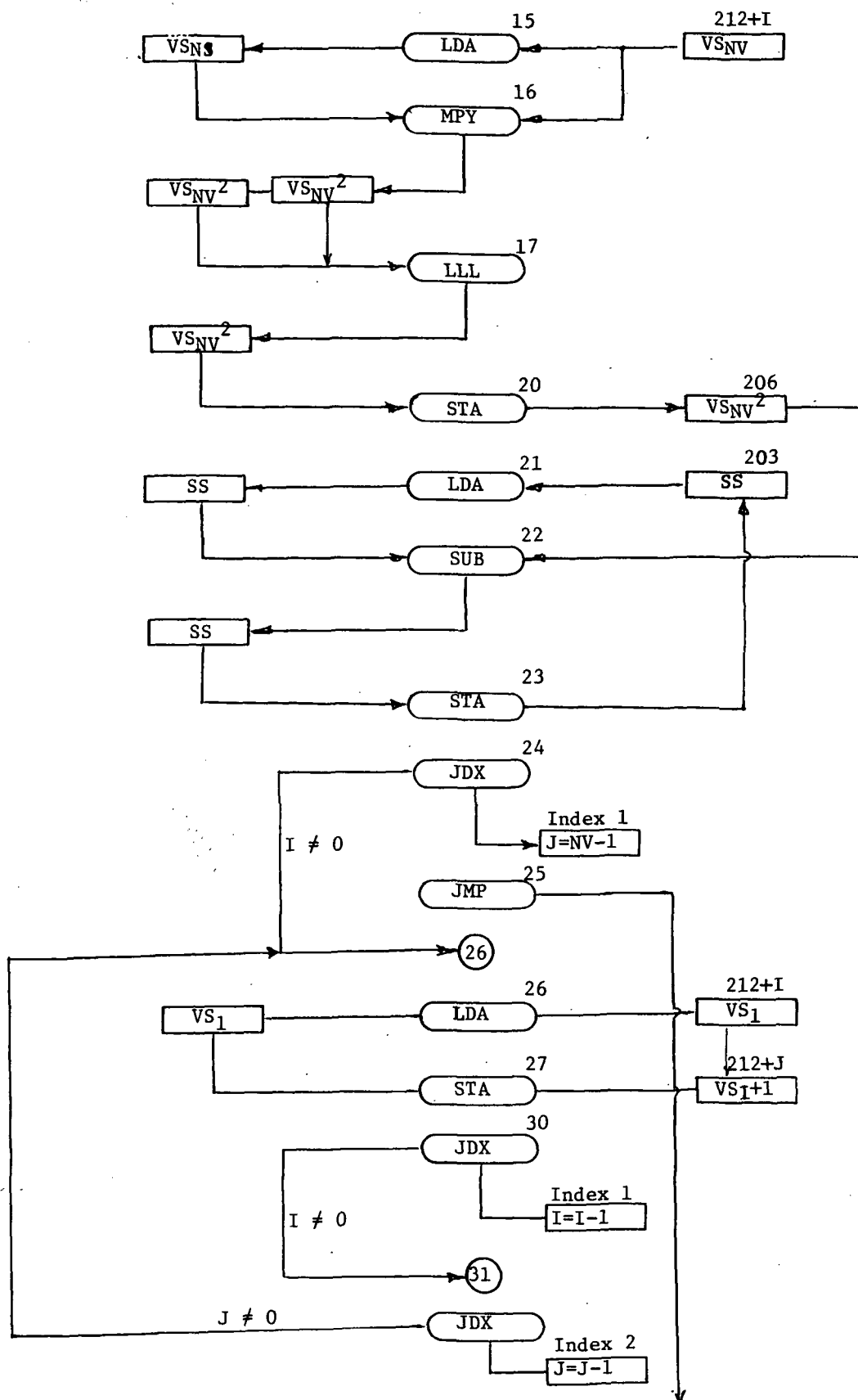
P	Instruction	MNEM	Description
00010	73 200 201	LDX	Set Index 1 = NV
00011	73 400 201	LDX	Set Index 2 = NV
00012	55 000 202	LDA	Load S
00013	67 200 212	SUB	Subtract VS_{NV} ($S = S - VS_{NV}$)
00014	41 000 202	STA	Store S
00015	55 200 212	LDA	Load VS_{NV}
00016	64 200 212	MPY	Multiply by VS_{NV} (VS_{NV}^2)
00017	16 000 027	LLL	Logical left shift 23 bit
00020	41 000 206	STA	Store VS_{NV}^2
00021	55 000 203	LDA	Load SS
00022	67 000 206	SUB	Subtract VS_{NV}^2 ($SS - VS_{NV}^2$)
00023	41 000 203	STA	Store SS
00024	71 200 026	JDX	Decrement Index 1 Jump to 26 if $\neq 0$
00025	44 000 032	JMP	Jump to 32
00026	55 200 212	LDA	Load VS_{N-1}
00027	41 400 212	STA	Store VS_N
00030	71 200 031	JDX	Decrement Index 1
00031	71 400 026	JDX	Decrement Index 2 Jump to 26 if $\neq 0$
00032	55 000 205	LDA	Load input value, V
00033	41 000 212	STA	Store V in VS_0
00034	66 000 202	ADD	Add S ($S + V$)
00035	41 000 202	STA	Store S
00036	11 000 028	LRL	Logical right shift 24 bits
00037	65 000 201	DIV	Divide by NV

DETERMINATION OF RUNNING VARIANCE

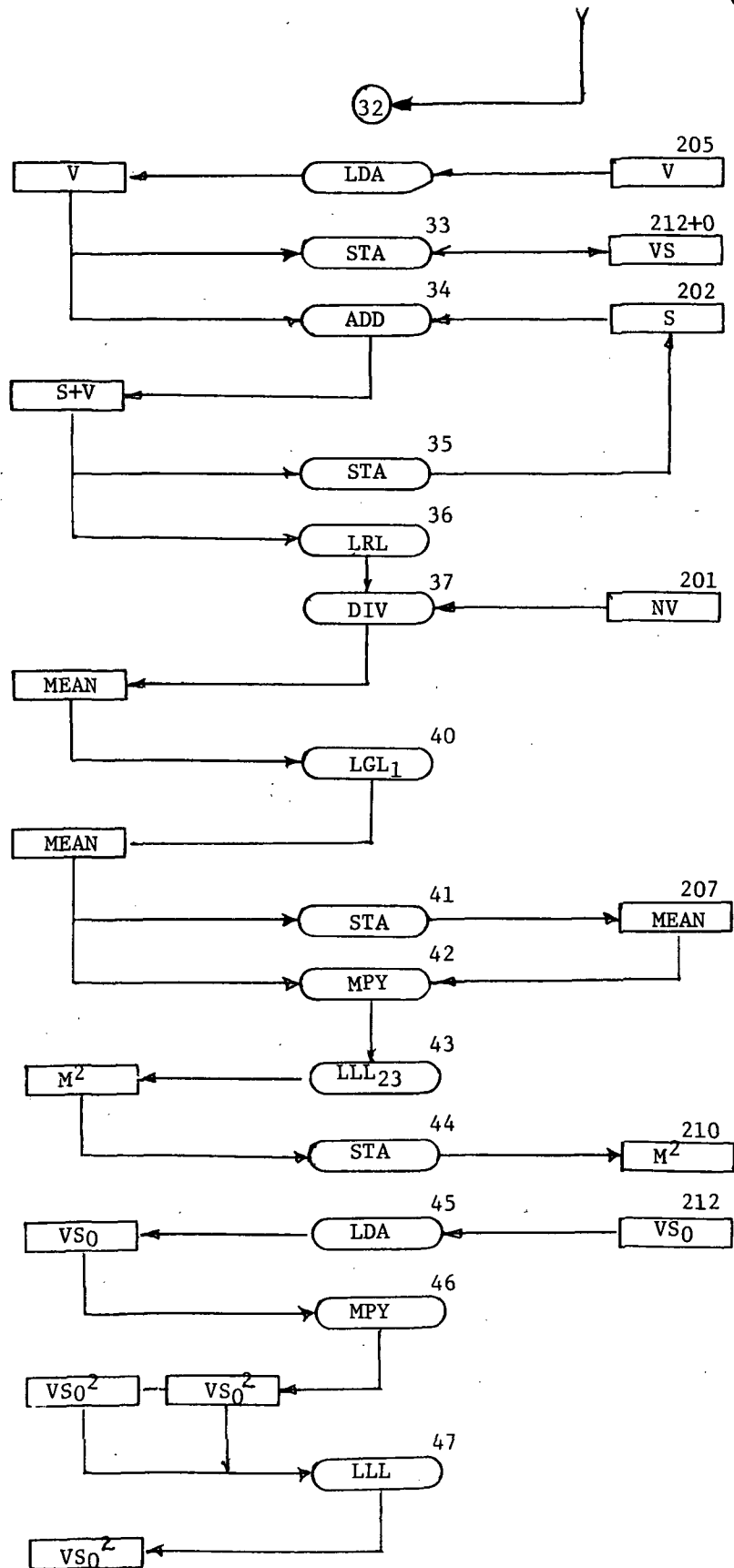
P	Instruction	MNEM	Description
00040	15 000 001	LGL	Logical left shift 1 bit
00041	41 000 207	STA	Store MEAN (S/NV)
00042	64 000 207	MPY	Multiply by MEAN
00043	16 000 027	LLL	Long left shift 23 bits
00044	41 000 210	STA	Store M2 ($MEAN^2$)
00045	55 000 212	LDA	Load VS_0
00046	64 000 027	MPY	Multiply by VS_0 (VS_0^2)
00047	16 000 027	LLL	Long left shift 23 bits
00050	66 000 203	ADD	Add SS ($SS + VS_0^2$)
00051	41 000 203	STA	Store SS
00052	11 000 028	LRL	Logical right shift 24 bits
00053	65 000 201	DIV	Divide by NV
00054	15 000 001	LGL	Divide by NV
00055	67 000 210	SUB	Subtract M2 ($SS/NV - M2$)
00056	41 000 211	STA	Store variance
00057	55 000 204	LDA	Load FLAG
00060	46 000 010	JAZ	Jump to 10 if FLAG = 0
00061	44 000 xxx	JMP	Jump out



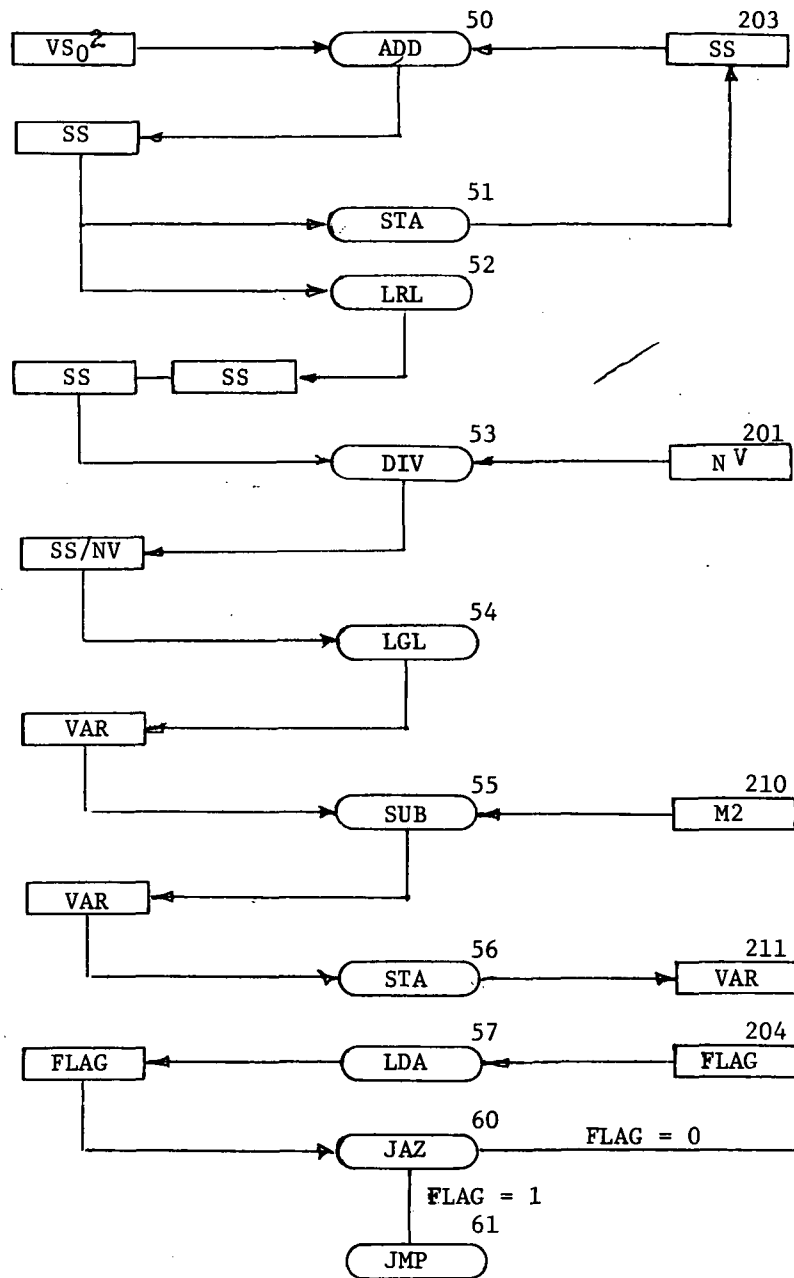
DETERMINATION OF RUNNING VARIANCE



C-33



DETERMINATION OF RUNNING VARIANCE



CONNECTIVE STRUCTURES

Compare value with limit - This type of structure reads the output of a given instrument (which might be a scientific experiment or an engineering sensor) and performs some sort of calculation on the input data. This calculation could be one in which a simple function is evaluated with the value read being one of the input variables or it could be one of the statistical routines. In any event, the result of the calculation is then compared with a limit which has been previously stored. If the result is larger than the limit, the difference is output as a signal of the desired event. This connective structure also samples a register for a stop flag which is used by the routine to exit.

In addition to the computation this connective structure requires 13 words of programming and one word of memory.

Compare a difference with a limit - This structure is much like the previous one except that two values are obtained and their difference is compared with the limit. In those instances where there is no certain knowledge as to an expected value, for example, the prevailing temperature, it can be calculated as well as the current temperature. The difference of a certain size then defines an anomalous condition. This structure also samples a register for a stop flag, which when set to one, signals the end of the run and resets the routine for the next usage.

In addition to two sets of computations, this structure requires 14 words of programming and one word of memory.

Fix a two dimensional position - This connective structure makes use of the previously described routine to find an anomalous condition. Once an anomaly has been found, it is checked to be sure that the anomaly is over a minimum width and less than a maximum width. Once these conditions are fulfilled, a provisional flag is set and the height is checked to determine that

the height of the anomaly falls between previously determined limits of size. When these conditions are met, the routine outputs the X and Y coordinates of the anomaly and resets itself for the next case.

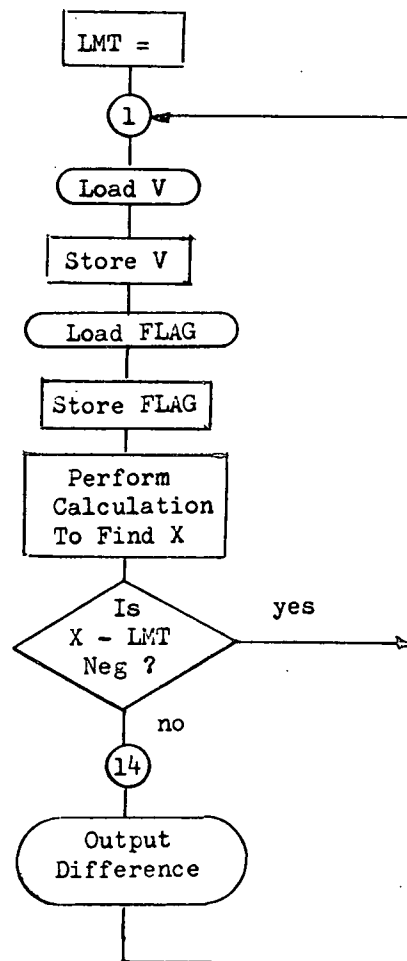
The routine requires 18 words of memory and 87 words of programming. These three connective structures are diagrammed on the following pages.

COMPARE A VALUE WITH A LIMIT

Memory Allocations

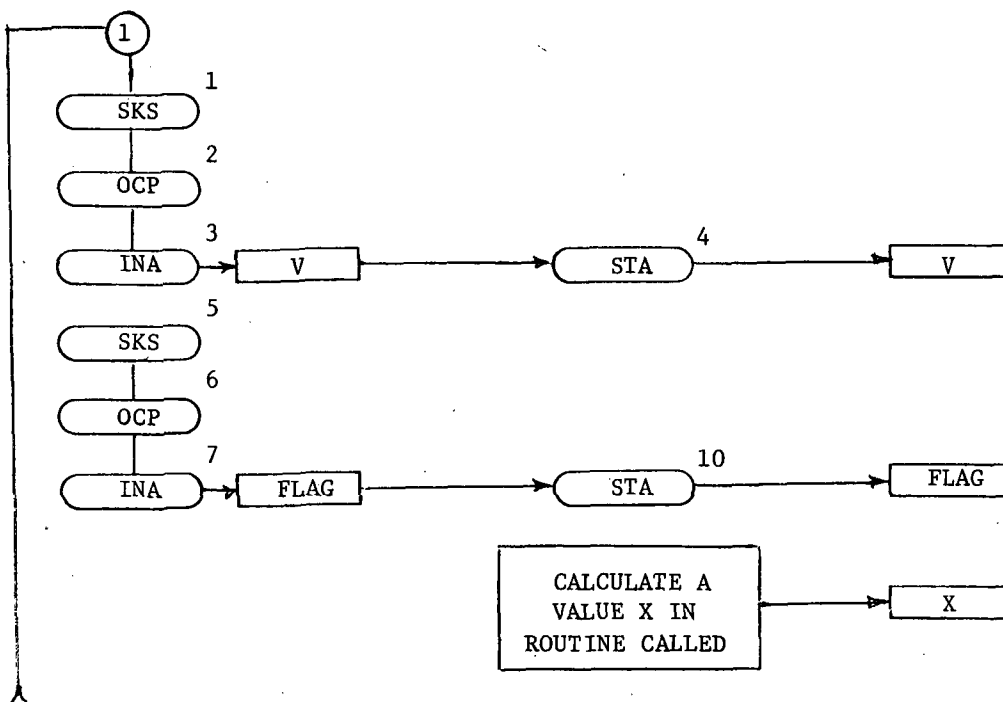
Location	Value	Symbol	Description
xxxxxx	----	V	Input Value
xxxxxx	0000 0000	FLAG	Stop Flag
xxxxxx	----	X	Calculated Value
00201	----	LMT	Preset Limit

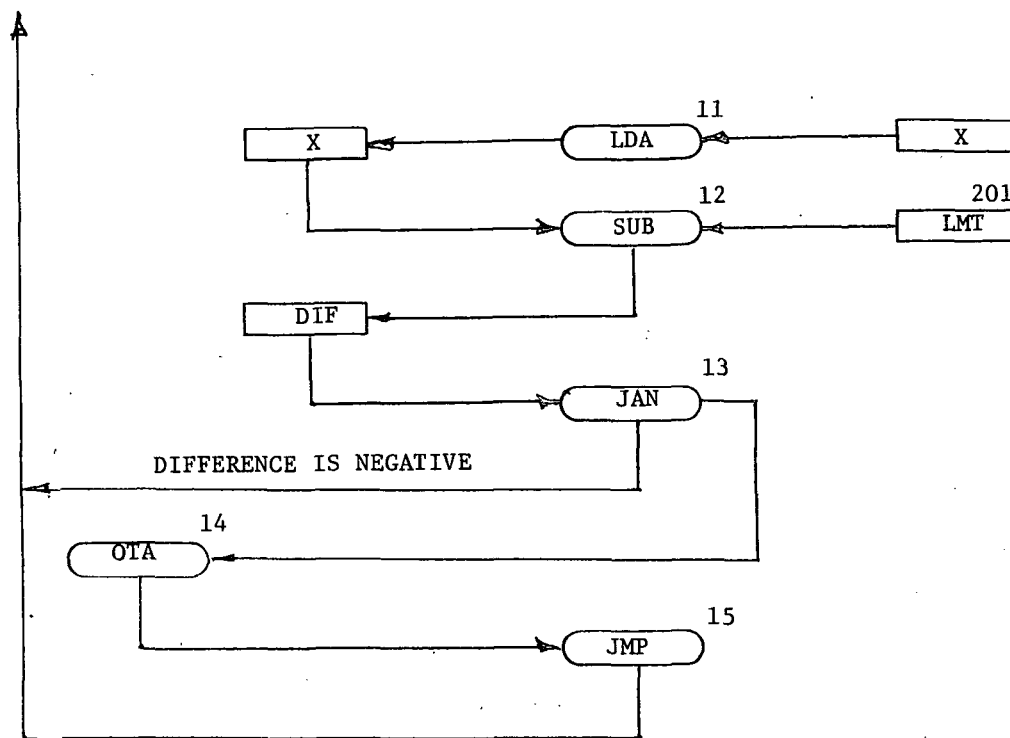
Memory is
provided for in
calculation routine



COMPARE A VALUE WITH A LIMIT

P	Instruction	MNEM	Description
00001	34 40x xxx	SKS	Input Value V
00002	35 40x xxx	OCP	
00003	32 40x xxx	INA	
00004	41 000 xxx	STA	Store V
00005	34 40x xxx	SKS	Input Stop FLAG
00006	35 40x xxx	OCP	
00007	32 40x xxx	INA	
00010	41 000 xxx	STA	Store FLAG
00011	55 000 xxx	LDA	Store calculated X
00012	67 000 201	SUB	Subtract LMT from X
00013	47 000 001	JAN	Jump to 1 if Difference is Negative
00014	30 40x xxx	OTA	Output Difference
00015	44 000 001	JMP	Jump to 1



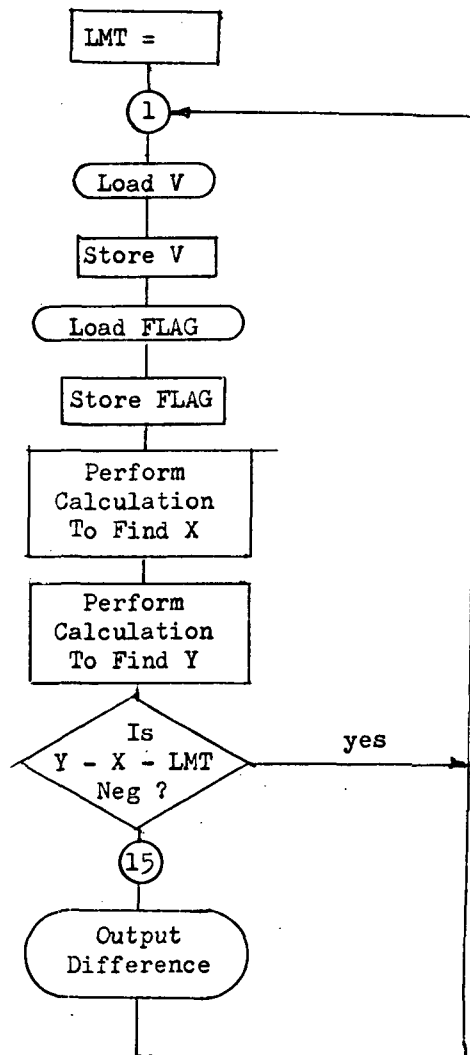


COMPARE A DIFFERENCE WITH A LIMIT

Memory Locations

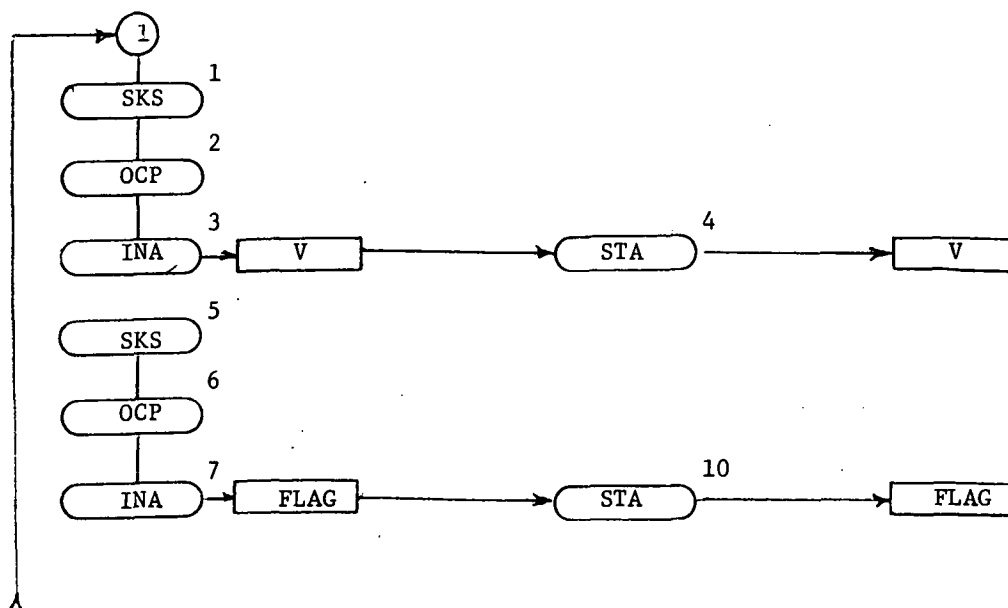
Location	Value	Symbol	Description
xxxxxx	----	V	Input value
xxxxxx	0000 0000	FLAG	Stop FLAG
xxxxxx	----	X	Calculated
xxxxxx	----	Y	Values
00201	----	LMT	Preset limit

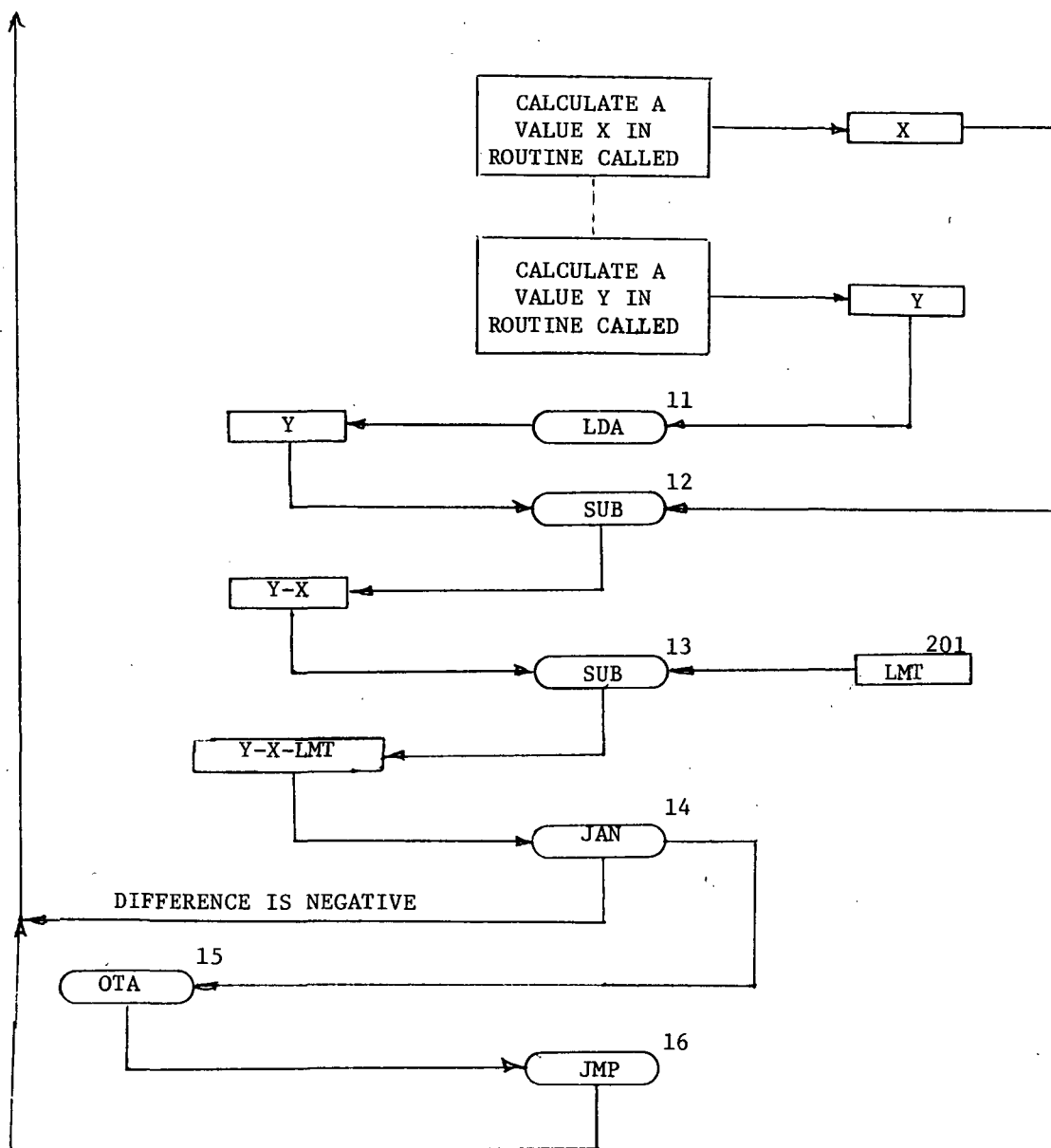
Memory
provided
for by
routine
called



COMPARE A DIFFERENCE WITH A LIMIT

P	Instruction	MNEM	Description
00001	34 40x xxx	SKS	Input Value V
00002	35 40x xxx	OCP	
00003	32 40x xxx	INA	
00004	41 00x xxx	STA	Store Value V
00005	34 40x xxx	SKS	Input Stop FLAG
00006	35 40x xxx	OCP	
00007	32 40x xxx	INA	
00010	41 00x xxx	STA	Store FLAG
00011	55 000 xxx	LDA	Load Calculated Value Y
00012	67 000 xxx	SUB	Subtract Calculated X
00013	67 000 201	SUB	Subtract LMT
00014	47 000 001	JAN	Jump to 1 if Negative
00015	30 40x xxx	OTA	Output Difference
00016	44 000 001	JMP	Jump to 1

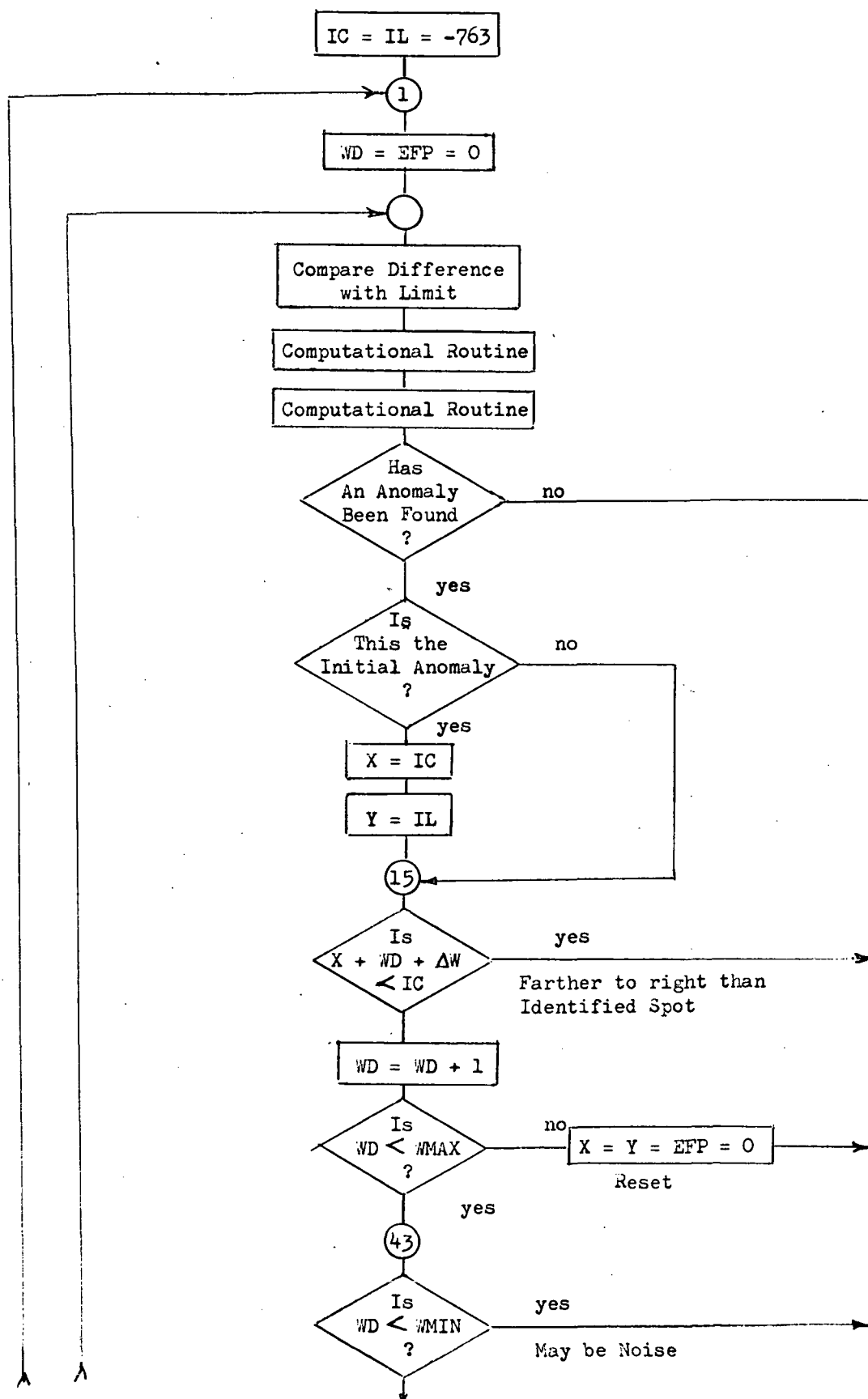


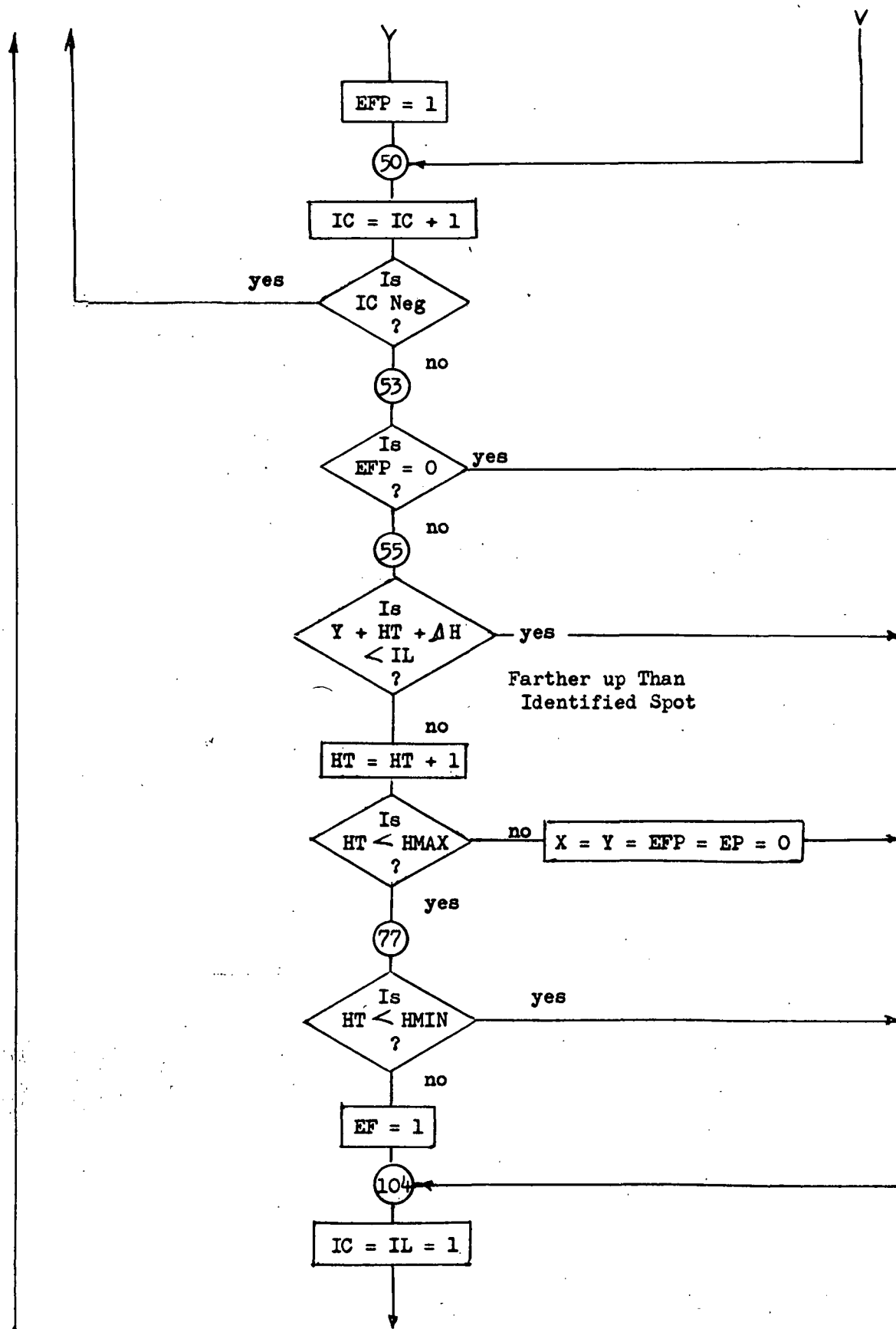


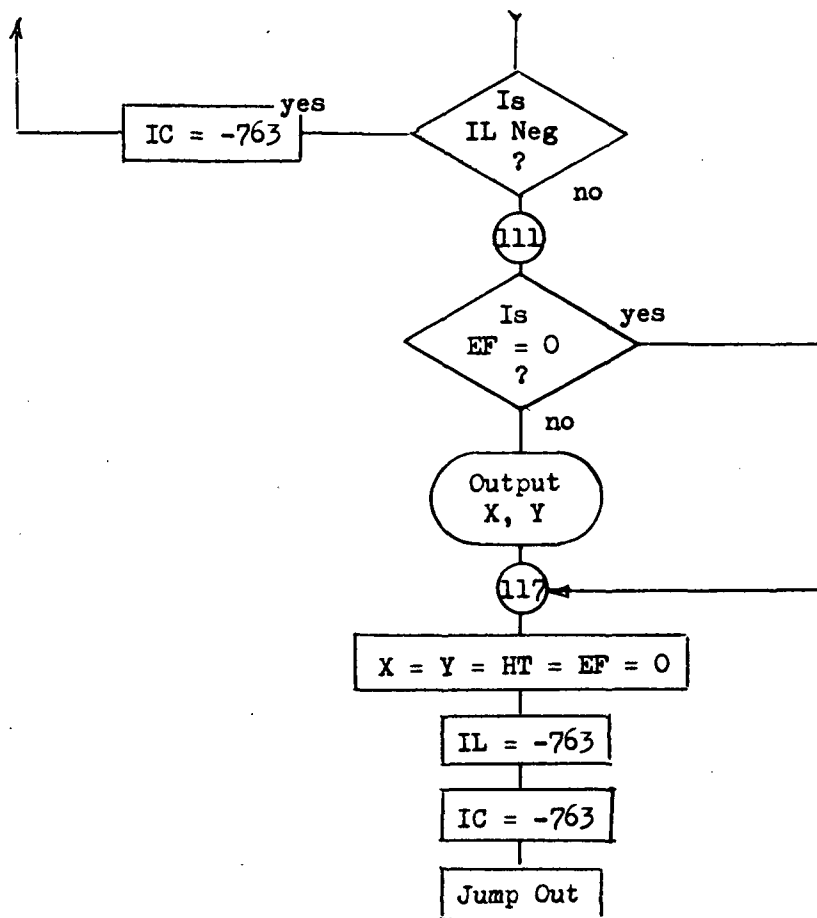
FIX A TWO DIMENSIONAL POSITION

Memory Allocations

Location	Initial Value	Symbol	Description
00201	0000 0000	WD	Width of anomaly
00202	0000 0000	EFP	Event FLAG provisional
00203	0000 0000	X	Left edge of anomaly
00204	0000 0000	Y	Bottom edge of anomaly
00205	0107 7015	IC	Index of column (initially -500)
00206	0000 0764	ICT	Total no. of pixels - columns
00207	0107 7015	IL	Index of line (initially -500)
00210	0000 0764	JLT	Total no. of pixels - lines
00211	---- ----	-IC	Negative IC
00212	0000 0005	DW	Delta width (max chg/line)
00213	0000 0050	WMAX	Maximum width of anomaly
00214	0000 0000	HT	Height of anomaly
00215	0000 0050	HMAX	Maximum height of anomaly
00216	0000 0000	EF	Event FLAG
00217	0000 0010	HMIN	Minimal height of anomaly
00220	0000 0010	WMIN	Minimum width of anomaly
00221	0000 0005	DH	Delta height (max chg/line)
00222	0107 7015		IC/IL Reload

FIX A TWO DIMENSIONAL POSITION

FIX A TWO DIMENSIONSL POSITION

FIX A TWO DIMENSIONAL POSITION

FIX A TWO DIMENSIONAL POSITION

P	Instruction	MNEM	Description
00001	01 000 000	CRA	Clear "A" register
00002	41 000 201	STA	Store Zero in WD
00003	41 000 202	STA	Set EFP equal to Zero
	Compare dif. to limit = 15 Running mean = $24 \times 2 = 48$ 63 Last statement JAN Directs program to 50 If dif. is less than limit		
00004	55 000 203	LDA	Load X
00005	66 000 204	ADD	Add Y
00006	45 000 015	JAP	Jump to 15 if either X or Y > 0
00007	55 000 205	LDA	Load index IC
00010	66 000 206	ADD	Add ICT to get + IC
00011	41 000 203	STA	Store IC in X
00012	55 000 207	LDA	Load JL
00013	66 000 210	ADD	Add JLT to get + IL
00014	41 000 204	STA	Store IL in Y
00015	55 000 205	LDA	Load IC
00016	66 000 206	ADD	Add ICT
00017	21 000 000	ICA	Find two's complement
00020	41 000 211	STA	Store -IC
00021	66 000 203	ADD	Add X (X-IC)
00022	66 000 201	ADD	Add WD (X+WD-IC)
00023	66 000 212	ADD	Add DW (X+WD+AD-IC)
00024	47 000 050	JAN	Jump to 50 if neg
00025	55 000 203	LDA	Load X
00026	67 000 212	SUB	Subtract DW (X-DW)
00027	66 000 211	ADD	Add -IC (X-DW-IC)

FIX A TWO DIMENSIONAL POSITION

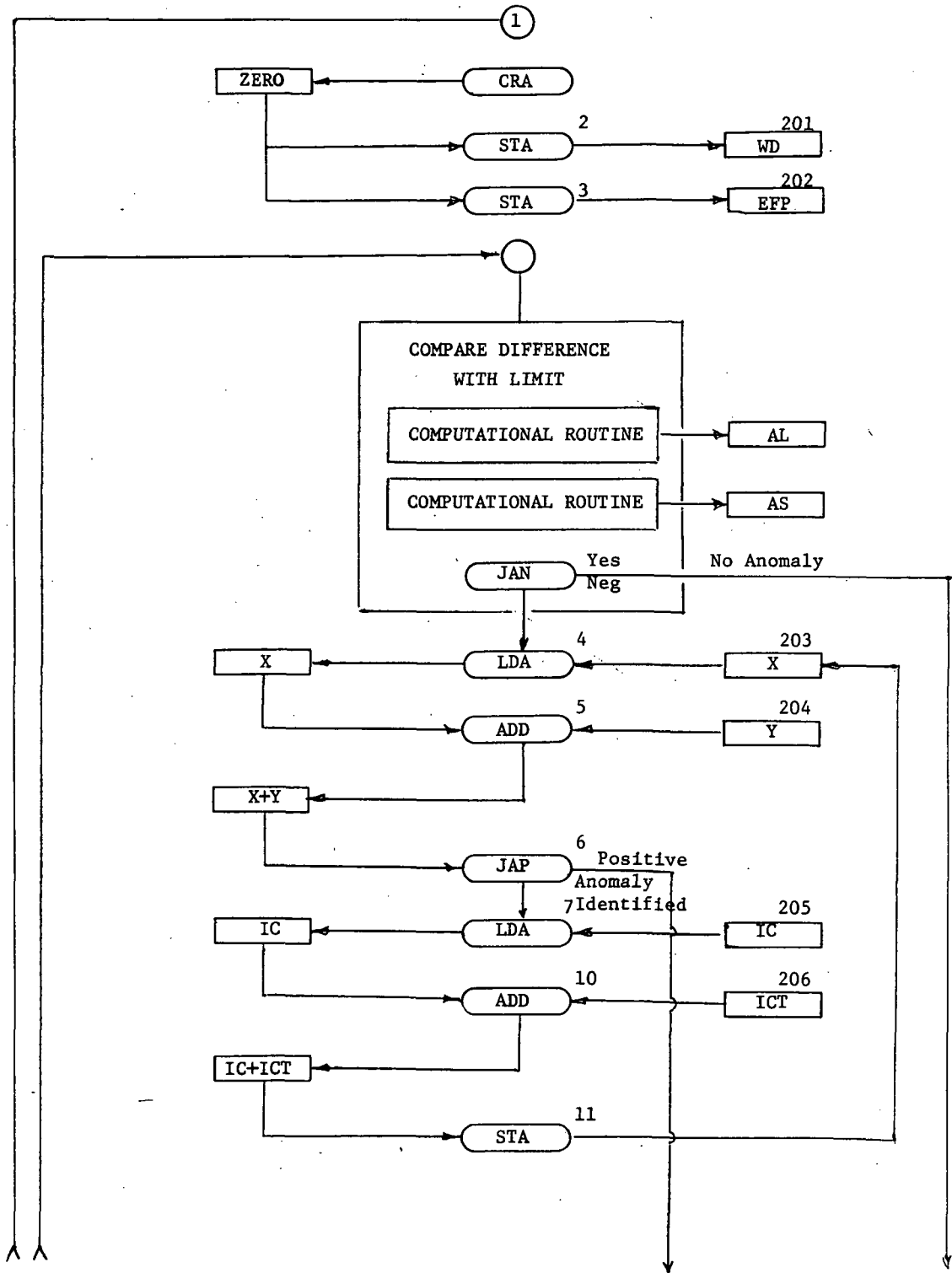
P	Instruction	MNEM	Description
00030	47 000 050	JAN	Jump to 50 if neg
00031	55 000 201	LDA	WD Loaded
00032	24 000 001	AAJ	Add Immediate (WD+1)
00033	41 000 201	STA	Store WD (width)
00034	67 000 213	SUB	Subtract NMAX (WD-WMAX)
00035	47 000 043	JAN	Jump to 43 if negative
00036	01 000 000	CRA	Clear "A" register
00037	41 000 203	STA	Set X to zero
00040	41 000 204	STA	Set Y to zero
00041	41 000 202	STA	Set EFP to zero
00042	44 000 050	JMP	Jump to 50
00043	55 000 201	LDA	Load WD
00044	67 000 220	SUB	Subtract WMIN (WD-WMIN)
00045	47 000 050	JAN	Jump to 50 if negative
00046	25 000 111	LAI	Load 1's immedite
00047	41 000 202	STA	Store 1's in EFP
00050	72 000 205	AAS	Augment IC and skip if negative
00051	44 000 053	JMP	Jump to 53
00052	44 000 XXX	JMP	Jump to X start or compare
00053	55 000 202	LDA	Load EFP
00054	40 000 104	JAZ ²	Jump to 104 if EFP is zero
00055	55 000 207	LDA	Load IL
00056	66 000 210	ADD	Add ILT
00057	21 000 000	TCA	Two's complement (-IL)

FIX A TWO DIMENSIONAL POSITION

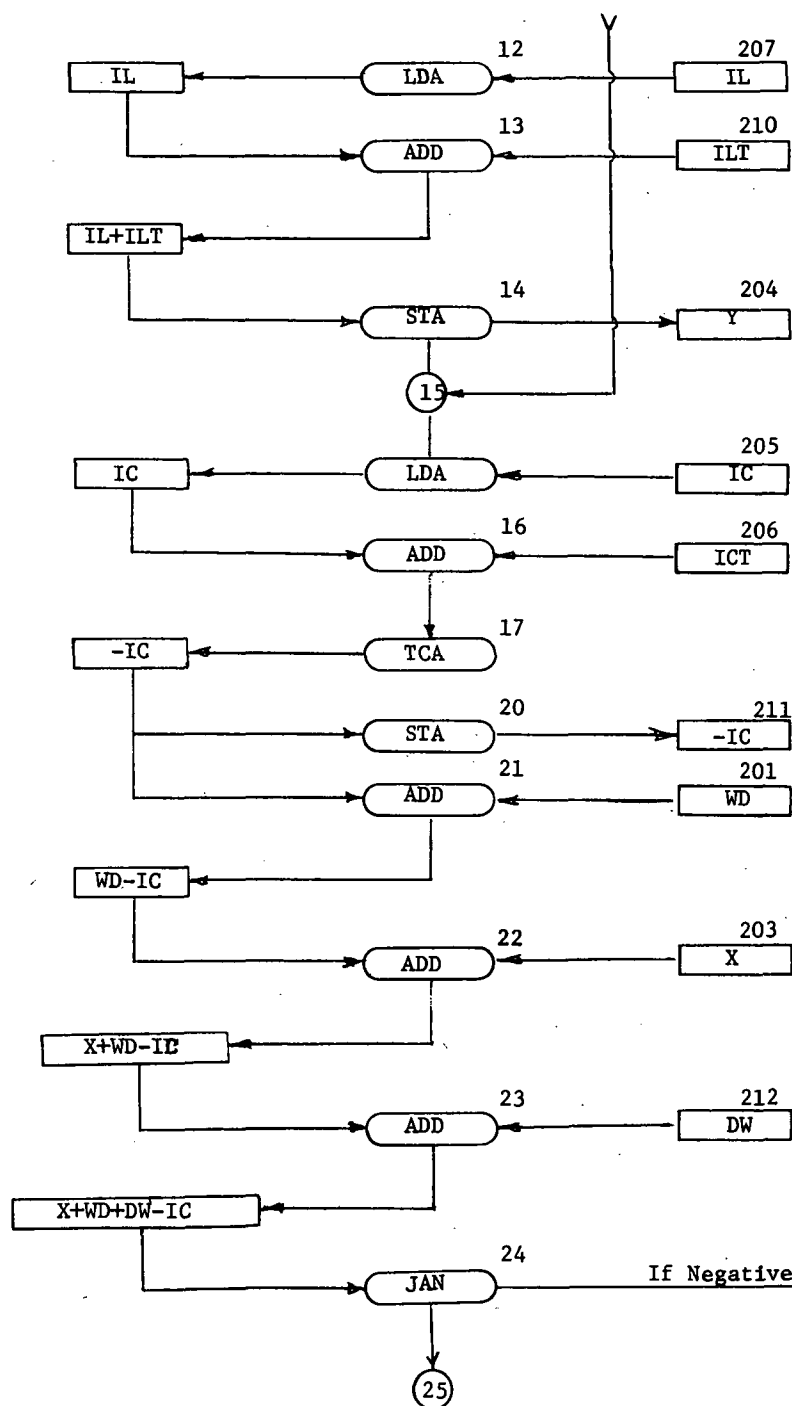
P	Instruction	MNEM	Description
00060	66 000 204	ADD	Add Y (Y-IL)
00061	66 000 214	ADD	Add HT (Y+HT-IL)
00062	66 000 221	ADD	Add DH (Y+HT+DH-IL)
00063	47 000 104	JAN	Jump to 104 if negative
00064	55 000 214	LDA	Load HT
00065	24 000 001	AAI	Add Immediate (HT+1)
00066	41 000 214	STA	Store HT
00067	67 000 215	SUB	Subtract HMAX (HT-HMAX)
00070	47 000 077	JAN	Jump to 77 if negative
00071	01 000 000	CRA	Clear "A" register
00072	41 000 203	STA	Set X = zero
00073	41 000 204	STA	Set Y = zero
00074	41 000 202	STA	Set EFP = zero
00075	41 000 216	STA	Set EF = zero
00076	44 000 104	JMP	Jump to 104
00077	55 000 214	LDA	Load HT
00100	67 000 217	SUB	Subtract HMIN (HT-HMIN)
00101	47 000 104	JAN	Jump to 104 if negative
00102	25 000 007	LAI	Load Immediate with 1's
00103	41 000 216	STA	Store 1's in EF
00104	72 000 207	AAS	Augment IL and skip if negative
00105	44 000 111	JMP	Jump to 111
00106	55 000 222	LDA	Load (-763)
00107	41 000 205	STA	Set IC = -763

FIX A TWO DIMENSIONAL POSITION

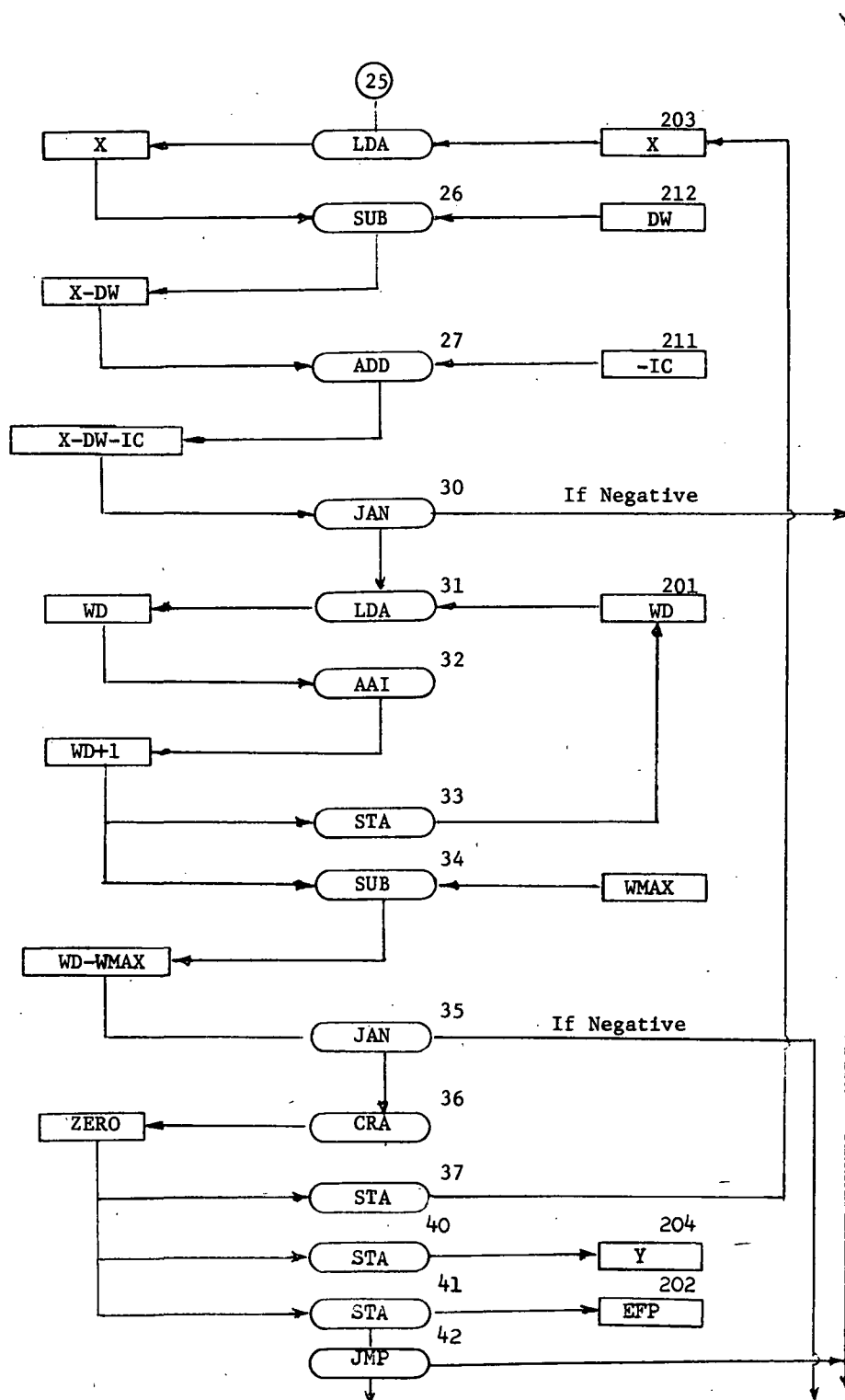
P	Instruction	MNEM	Description
00110	44 000 001	JMP	Jump to 1
00111	55 000 216	LDA	Load EF
00112	46 000 117	JAZ	Jump to 117 if EF = 0
00113	55 000 203	LDA	Load X
00114	30 40X XXX	OTA	Output X
00115	55 000 204	LDA	Load Y
00116	30 40X XXX	OTA	Output Y
00117	01 000 000	CRA	Clear "A" register
00120	41 000 203	STA	Set X = zero
00121	41 000 204	STA	Set Y = zero
00122	41 000 214	STA	Set HT = zero
00123	41 000 216	STA	Set EF = zero
00124	55 000 222	LDA	Load Immediate (-763)
00125	41 000 207	STA	Set IL = -763
00126	41 000 205	STA	Set IC = -763
00127	44 0XX XXX	JMP	Jump out of routine

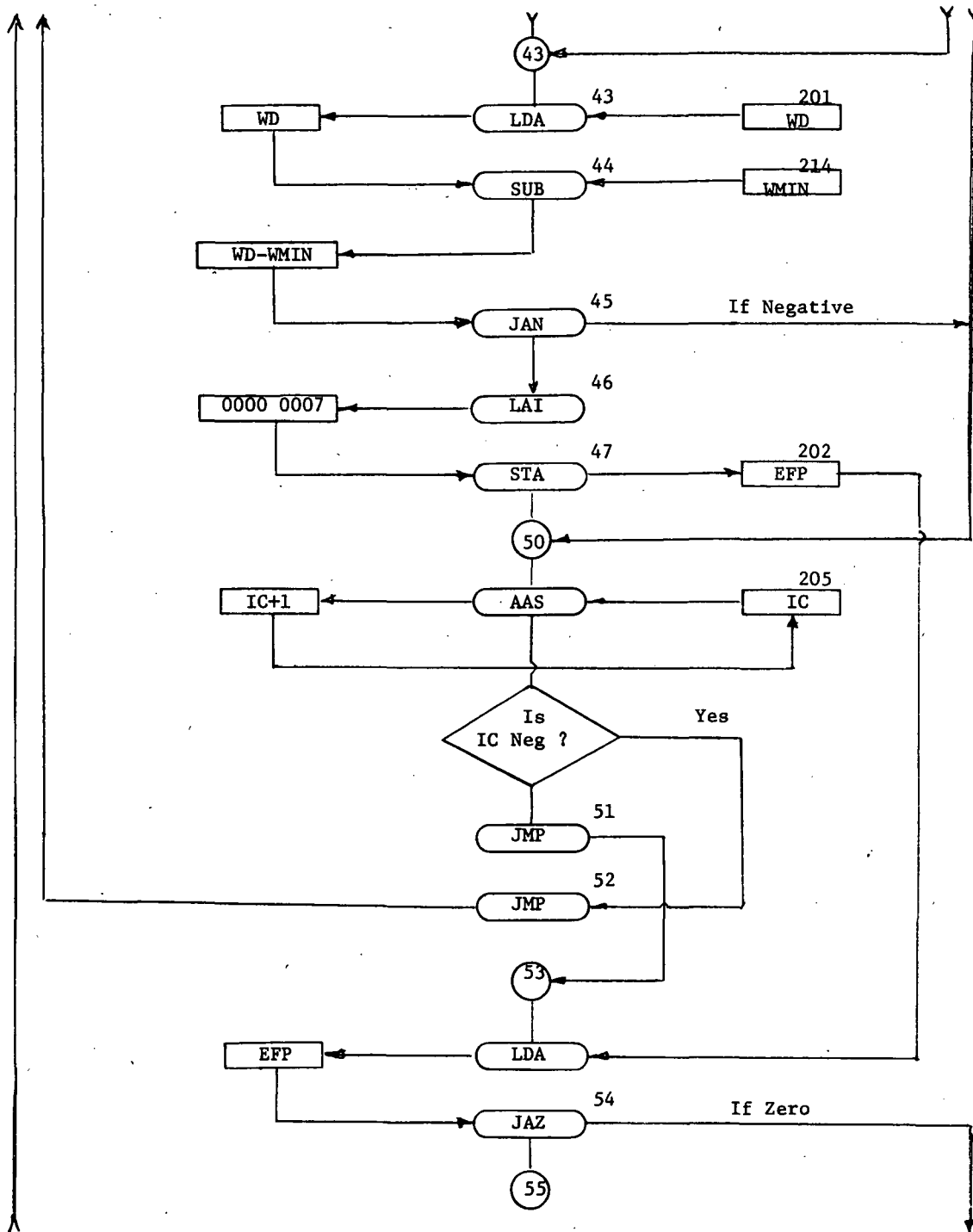


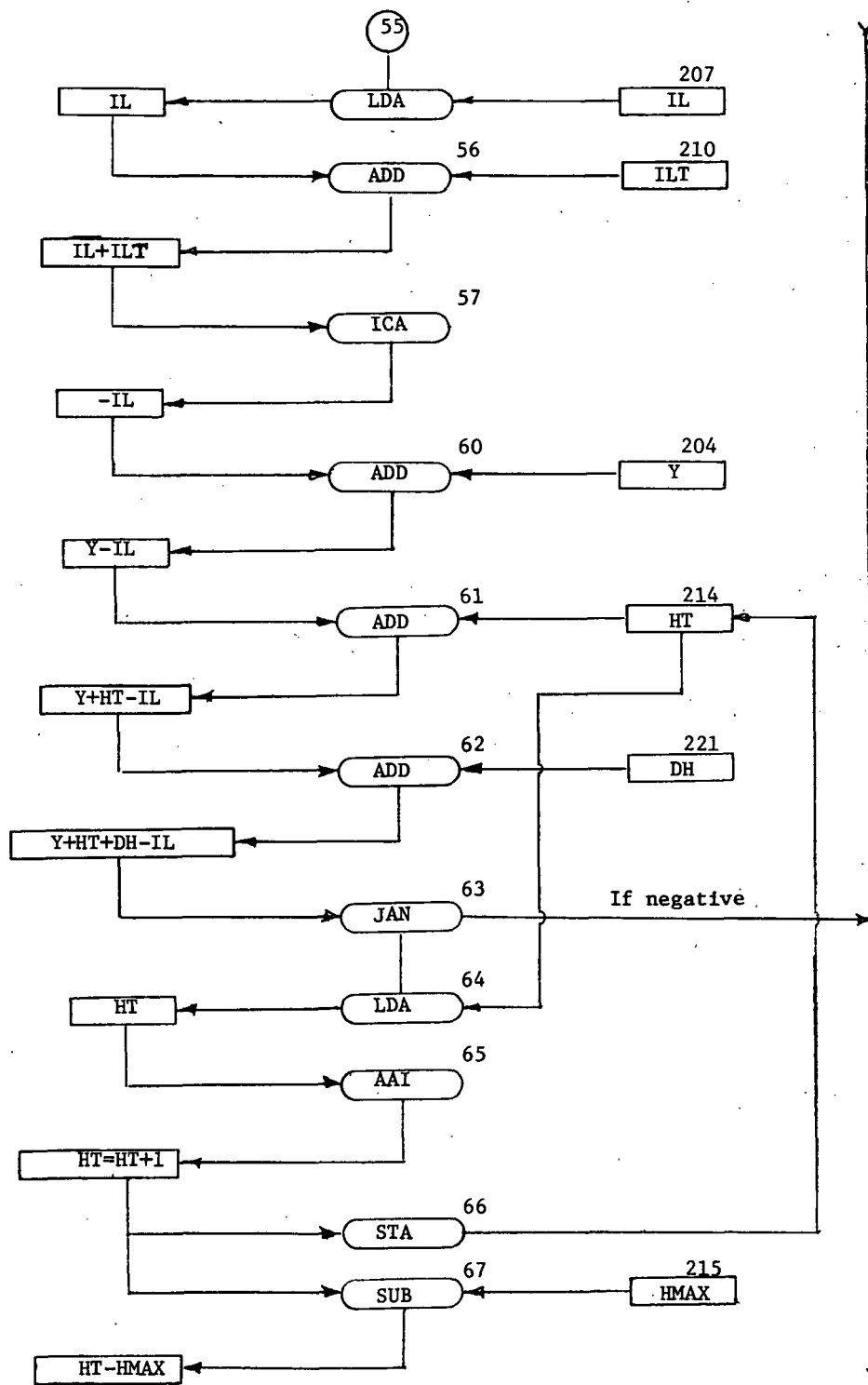
FIX A TWO DIMENSIONAL POSITION



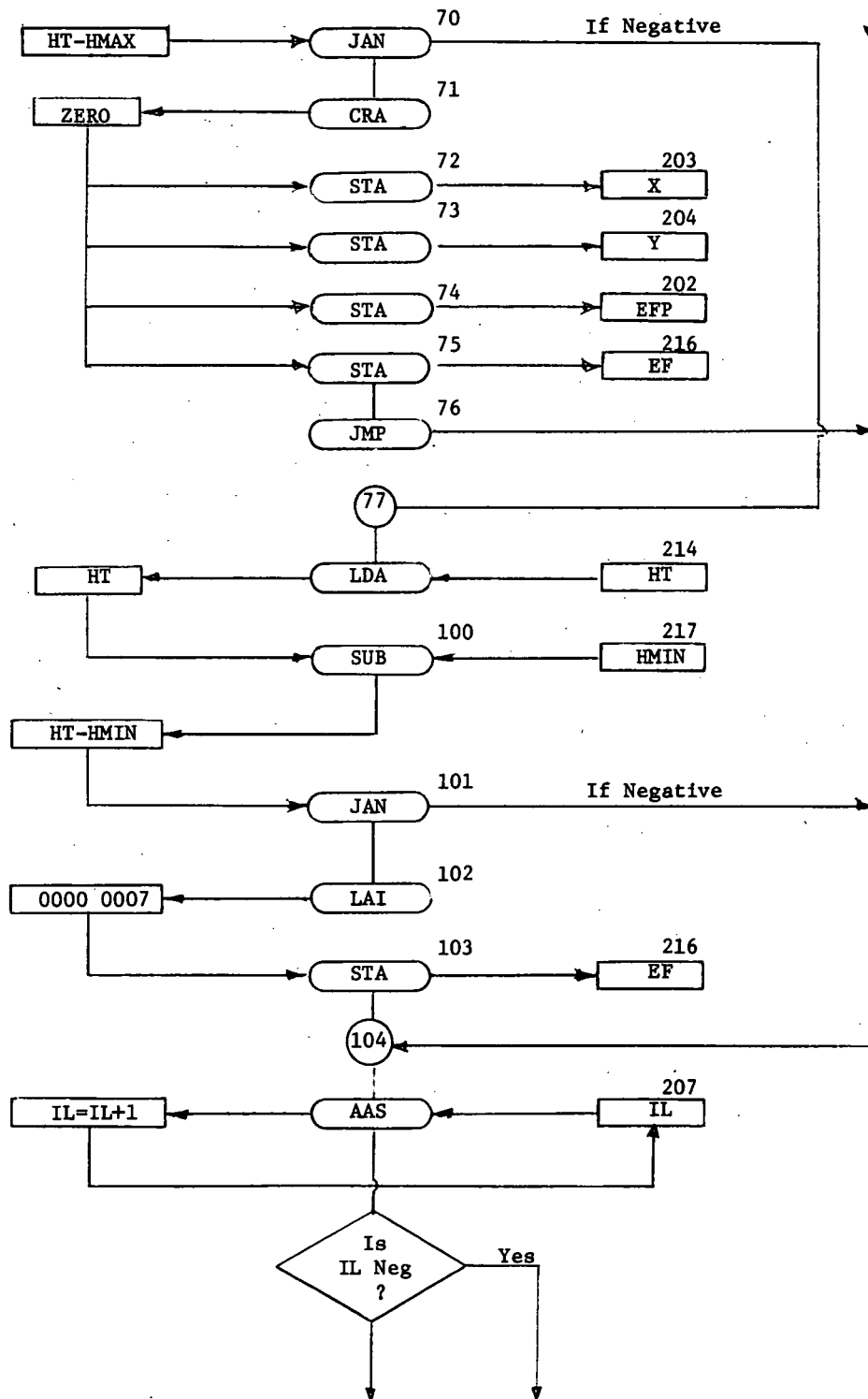
FIX A TWO DIMENSIONAL POSITION



FIX A TWO DIMENSIONAL POSITION



FIX A TWO DIMENSIONAL POSITION



FIX A TWO DIMENSIONAL POSTION

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