Assessment of Impact on Integrated Science Return from the 1992 Mars Observer Mission: Letter Report

Committee on Planetary and Lunar Exploration, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council

ISBN: 0-309-12298-8, 23 pages, 8 1/2 x 11, (1988)

NATIONAL RESEARCH COUNCIL

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES

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July 12, 1988

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Dear Geoff:

This letter is in response to your request of May 24, 1988, that the Committee on Planetary and Lunar Exploration (COMPLEX) provide an assessment of the impact on integrated science return from the 1992 Mars Observer (MO) mission if the agency were to descope or delete instruments from the currently approved science payload. It is our understanding that the OSSA has decided that immediate steps must be taken to reduce the cost of Mars Observer, and that cost escalation is judged by the agency to constitute a programmatic crisis so severe that it explicitly threatens the selected and confirmed science instrument payload of this mission.

The summary conclusion of the committee, based on discussions and evaluation in the body of this report, is that reduction of present mission scope by deletion of any instrument would have seriously deleterious consequences for the return of science data. The intrinsic seriousness of this situation is further compounded, at this time and for this mission in particular, by the decade-long hiatus in the launch of all U.S. planetary missions, the sharpening international scientific focus on Mars as a prime target of planetary exploration, the likelihood that this mission represents the only opportunity for investigation of Mars by this nation in the coming decade, and the superb individual and synergistic science capabilities of the instruments originally selected for it. The implications of a decision to compromise these capabilities or to postpone the mission further are thus especially grave.

Proposed agency actions to reduce substantially the scope of the Mars Observer mission have direct impacts on implementation of the COMPLEX strategy for scientific exploration of the planet. For this reason your formal request to the committee to assess the science implications of these cost-reduction options is regarded as fully consistent with the ongoing responsibilities of the Space Science Board and the effective operation of the advisory interface between the NRC and NASA.

Inasmuch as the original Mars Observer instrument payload selection was based on its ability to address, individually and collectively, the committee's Mars exploration strategy, science objectives, and measurement requirements, it would be inappropriate in this situation for COMPLEX to attempt to provide explicit recommendations for removal of instruments. Any modification of mission objectives or schedule is ultimately a programmatic matter, which must be considered and decided by agency management in a fully informed way. It is clear from your request (quoted below) for scientific assessment of the consequences of changes in mission scope, rather than for specific recommendations on payload modification, that you share this view.

SUMMARY AND INTERPRETATION OF REQUEST

> . . . I would like . . . to request that, at your scheduled committee meeting in Santa Fe in June, you prepare and provide us at the earliest opportunity your assessment report of science loss of this particular mission and of its possible effects on the longer-range program of Mars exploration, including the science objectives for surface exploration and sample return. I assume that, as in previous requests of this kind, your assessment will be in terms of the current strategy for Mars and will preserve the distinction between the strategy and programmatic considerations.

This request separates the scientific from the programmatic elements of the problem, and is consistent with our view that the role of COMPLEX in this matter is to advise the agency on the mission-related and longer term science implications of proposed reductions in the Mars Observer instrument complement. It is clear from the priorities assigned by COMPLEX to various elements of our martian exploration strategy, discussed in the body of this report, that consideration of longer term implications must focus in particular on future in situ surface science and sample return missions. In this context, COMPLEX considers that we have been asked to provide the following:

1. Our perception of the scientific impact of three candidate Mars Observer reduction options--specifically, the descoping of the radar altimeter and radiometer (RAR), plus deletion of a second major instrument, either the Mars Observer camera (MOC) or the thermal emission spectrometer (TES) or the visual and infrared mapping spectrometer (VIMS)--presented by the Solar System Exploration Division to project management, principal investigators, and interdisciplinary scientists, and to several members of COMPLEX, at a project review at NASA headquarters on May 31, 1988.

2. Our assessment of the degree to which Mars Observer, with its science capabilities reduced by implementation of one of these options, would then address the priority-ranked science objectives recommended by the Space Science Board for exploration of Mars.

To these two tasks the committee adds two more tasks:

3. Discussion and evaluation of the four other science instruments or facilities in the current payload--the gamma ray spectrometer (GRS), the pressure modulator infrared radiometer (PMIRR), the magnetometer (MAG), and radio science (RS).

4. Comments on a different option that, in our understanding, is also being considered by the agency: delay of Mars Observer until 1994, with the presumption that the mission would launch at that time with its full baseline instrument payload.

COMMITTEE DELIBERATIONS

This letter report was prepared by COMPLEX at its meeting of June 13 to 17, 1988, in Santa Fe, New Mexico, in response to the above request from NASA. It is presented as an assessment of both the current scientific scope of the Mars Observer mission, and the proposed reductions of that scope, in the context of the published Space Science Board exploration strategy for Mars. The committee was assisted in our deliberations by written materials produced by members of the project (including relevant sections of the instrument proposals), by oral and written information conveyed to eight committee members at the May 31, 1988, Mars Observer Project Review at NASA headquarters, and by invited presentations to the committee at the Santa Fe meeting by the mission's principal investigators or team members for the GRS, MOC, PMIRR, RAR, TES, and VIMS experiments. Presentations from representatives of the MAG and RS experiments were considered by the committee not to be necessary. An additional invited presentation, on the potential for stereophotogrammetric recovery of accurate topographic information from MOC images, was made at the Sante Fe meeting by R. Gaskell of the Jet Propulsion Laboratory.

SUMMARY OF RESPONSE

It is the position of COMPLEX that Mars Observer can no longer be regarded as an Observer-class mission, and that the range and quality of information return from the mission must be expected to be commensurate with its cost and instrumental sophistication. We conclude from the assessment provided in this report that, in the context of the science priorities established by the Space Science Board for orbital exploration of Mars, the anticipated data return from Mars Observer with its present instruments and launch schedule is responsive in full degree to this expectation and to the need for return of its data in the most timely possible way. It is therefore the recommendation of the Committee that Mars Observer be launched in 1992 with its current science instrument payload and experimental objectives essentially intact.

If the agency determines that as a consequence of the current financial crisis there are absolutely no alternatives to a reduction in the present scientific scope of the Mars Observer mission, and carries out one of the *proposed* descoping options *with the most careful attention to the scientific penalties incurred and with full and responsible commitment to minimizing the consequences of these penalties*, COMPLEX will *not* argue that the mission is no longer scientifically viable. But we make no specific recommendations concerning ordering of choices to be made in implementing this action.

1. COMPLEX EXPLORATION STRATEGY AND SCIENTIFIC OBJECTIVES FOR MARS

The current exploration strategy, priority-ranked science objectives, and measurement requirements for Mars are developed and set out in the COMPLEX-SSB report Strategy for Exploration of the Inner Planets: 1977-1987 (Space Science Board, 1978). Primary objectives in order of scientific priority for the continued (post-Viking) exploration of Mars are as follows:

1. To investigate local areas intensively (a) to establish the chemical, mineralogical, and petrological character of different components of the surface material, representative of the known diversity of the planet; (b) to establish the nature and chronology of major surface-forming processes; (c) to determine the distribution, abundance, and sources and sinks of volatile materials, including an assessment of the biological potential of the martian environment, now and during past epochs; and (d) to establish the interaction of the surface material with the atmosphere and its radiation environment.

2. To explore the structure and general circulation of the Martian atmosphere.

3. To explore the structure and dynamics of the martian interior.

4. To establish the nature of the martian magnetic field and the character of the upper atmosphere and its interaction with the solar wind.

5. To establish the global chemical and physical characteristics of the martian surface.

In Section 2 of this report, the committee summarizes the objectives of the current Mars Observer mission, and in Section 3 we discuss and evaluate the MO objectives in the context of the COMPLEX science priorities for martian exploration.

2. MARS OBSERVER: MISSION OBJECTIVES AND CURRENT SCIENCE PAYLOAD

Mission Objectives and Individual Instrument Objectives

The following summary of mission objectives and individual instrument objectives is taken from the project material document "Mars Observer Science Options Review," JPL, May 31, 1988. More detailed statements of measurement capabilities and objectives, from the instrument proposals and presentations at the Santa Fe meeting, were also considered by the committee.

The published overall mission science objectives (not ranked by priority) are as follows:

1. Determine the global elemental and mineralogical character of the surface material.

2. Define globally the topography and gravitational field.

3. Establish the nature of the magnetic field.

4. Determine the time and space distribution, abundance, sources, and sinks of volatile material and dust over a seasonal cycle.

5. Explore the structure and aspects of the circulation of the atmosphere.

The individual instruments and instrumental objectives are as follows:

• Gamma Ray Spectrometer (GRS). (1) Determine the elemental composition of the surface of Mars with a spatial resolution of a few hundred kilometers through measurements of incident gamma-rays and albedo neutrons (H, O, Mg, Al, Si, S, Cl, K, Ca, Fe, Th, U); (2) determine hydrogen depth dependence in the top tens of centimeters; (3) determine the atmospheric column density; (4) determine the arrival time and spectra of gamma-ray bursts.

• Magnetometer (MAG). (1) Establish the nature of the magnetic field of Mars; (2) develop models for its representation that take into account the internal sources of magnetism and the effects of the interaction with the solar wind; (3) map the martian crustal remanent field using the fluxgate sensors and extend these in situ measurements with the remote capability of the electron reflectometer sensor; (4) characterize the solar wind/Mars plasma interaction; (5) remotely sense the martian ionosphere.

• Mars Observer Camera (MOC). (1) Obtain global synoptic views of the martian atmosphere and surface to study meteorological, climatological, and related surface changes; (2) monitor surface and atmospheric features at moderate resolution for changes on time scales of hours, days, weeks, months, and years; (3) systematically examine local areas at extremely high spatial resolution in order to quantify surface/atmosphere interactions and geological processes.

• Pressure Modulator Infrared Radiometer (PMIRR). (1) Map the three-dimensional and time-varying thermal structure of the atmosphere from the surface to 80-km altitude; (2) map the atmospheric dust loading and its global, vertical, and temporal variation; (3) map the seasonal and spatial variation of the vertical distribution of atmospheric water vapor to an altitude of at least 35 km; (4) distinguish between atmospheric condensates and map their spatial and temporal variation; (5) map the seasonal and spatial variability of atmospheric pressure; (6) monitor the polar radiation balance.

• Radio Altimeter and Radiometer (RAR). (1) Provide topographic height measurements with a vertical resolution better than 0.5 percent of the elevation change within the footprint; (2) provide RMS slope information over the (5 to 9 km) footprint; (3) provide surface brightness temperatures at 13.6 GHz with a precision of better than 2.5K; (4) provide well-sampled radar return waveforms for precise range corrections and the characterization of surface properties.

• Radio Science (RS). Atmosphere: (1) determine profiles of refractive index, number density, temperature, and pressure at the natural experimental resolution (~200 m) for the lowest few scale heights at high latitudes in both hemispheres on a daily basis; (2) monitor both short-term and seasonal variation in atmospheric stratification; (3) characterize the thermal response of the atmosphere to dust loading; (4) explore the thermal structure of the boundary layer at high vertical resolution (~10 m); (5) determine the height and peak plasma density of the daytime ionosphere; (6) characterize the small-scale structure of the atmosphere and ionosphere. Gravity: (1) develop a global, high-resolution model for the gravitational field; (2) determine both local and broad-scale density structure and stress state of the martian crust and upper mantle; (3) detect and measure temporal changes in low-degree harmonics of the gravitational field.

• Thermal Emission Spectrometer (TES). (1) Determine and map the composition of surface minerals, rocks, and ices; (2) study the composition, particle size, and spatial and temporal distribution of atmospheric dust; (3) locate water-ice and carbon dioxide condensate clouds and determine their temperature, height, and condensate abundance; (4) study the growth, retreat, and total energy balance of the polar cap deposits; (5) measure the thermophysical properties of the martian surface (thermal inertia, albedo) used to derive surface particle size and rock abundance; (6) determine atmospheric temperature, pressure, water vapor, and ozone profiles, and seasonal pressure variations.

• Visual and Infrared Mapping Spectrometer (VIMS). (1) Produce kilometer-resolution mosaics of the martian surface in 320 spectral channels for the purpose of identifying mineralogical and chemical units, studying the distribution of surface volatiles, and understanding the physical structure of the regolith; (2) produce a regional mapping of the martian surface at 10-km resolution in 10 wavelengths to extend the local interpretation to a global scale.

Proposed Additional Objectives for Mars Observer as a Mars Rover Sample Return Precursor Mission

Implementation of the top-priority COMPLEX objectives for Mars requires landing, the conduct of surface investigations, and the return of samples from the planet (see Section 3 below). Thus, the committee's endorsement of the Mars Observer mission, as originally conceived, is based on (1) the potential high quality and relevance of the science data returned and (2) the utility of those data in providing fundamental information to enable subsequent missions to address the highest science priority.

The Mars Rover Sample Return Science Working Group (MRSRSWG) presented a report and attendant recommendations on MO as a precursor for the Mars Rover Sample Return (MRSR) mission to the Mars Exploration Steering Group (G. Briggs, chair) on July 10, 1987. The first recommendation of this report affirms the ability of MO as currently planned to support a precursor role for MRSR, and the necessity for preserving its baseline capabilities. Subsequent recommendations deal with specific modifications, at various levels of priority, in the MO spacecraft, science instruments, and mission plan, which in the opinion of the MRSRSWG would be desirable to optimally fulfill this precursor role. Of these, the recommendations that specifically address science instruments are relevant to this report. It should be noted that in this context the explicit rationale for science instrument modifications is improvement in their capability to characterize potential future landing sites rather than increasing their science return per se, although the recommendations for instrument and mission profile changes, if implemented, would increase spatial resolution and extend the duration of the nominal mission, and thus would have this effect.

Three instruments--MOC, TES, and RAR--were identified by the MRSRSWG as most important for the recommended Mars Observer activity to characterize potential landing sites and identify hazards. <u>Ironically, all three are current candidates for descoping or deletion, and any one of the three announced options for modification of the instrument package would at best descope one and eliminate another</u>. Most attention was focused on the camera as the essential instrument in this context, and the hardware changes proposed by MRSRSWG for MOC deal largely with increasing the amount and contiguous extent of its high-resolution imaging capabilities. For TES, an increased spatial resolution (from 3 km to 650 m) was urged to characterize surface block distributions more effectively. The radar altimeter, with its high vertical resolution and small (5 to 9 km) footprint, was judged potentially useful for yielding information on local block frequency distributions, slopes, and general surface properties. We note that interpretations of TES and RAR observations in terms of block and slope frequency distributions and soil mechanics are not necessarily straightforward, and that the conclusions that can be drawn refer to average surface properties over the areas defined by their respective spatial resolutions. We further note that "spatial resolution," as used throughout this report, refers to the surface scale (meters or kilometers) reported by the smallest instrumental detection element (typically a pixel). Actual discernability of features and boundaries depends on a variety of instrumental (e.g., signal-to-noise) and viewing (e.g., sun angle and atmospheric conditions) factors.

An additional recommendation of the MRSRSWG dealt with a science-related addition to the current Mars Observer payload. We quote from their report:

> . . . the best source of close-up information on the Martian surface between now and the MRSR mission is expected to be data from Soviet missions. The most voluminous data are likely to be those from balloons, which are expected to fly 300 to 500 km a day, nominally for 10 days. The volume of imaging data from the balloons depends on the data link. Addition of a small (10 cm) relay antenna on MO could increase this volume of balloon data by a factor of 10. Because these data will so significantly increase our knowledge of the frequency of near-surface hazards [and our scientific understanding of the physical characteristics of the surface (note added)] and because of the potential use of the data for calibrating TES, we recommend that the project vigorously explore the possibility of using MO as a relay for the U.S.S.R. Mars '92 [now '94 (note added)] balloons.

The committee is uncertain of the agency response to this recommendation. It appears attractive for a variety of reasons, relating to overall science return and international coordination in space exploration as well as to the matter at hand.

The overarching recommendation of the MRSRSWG was that: "the role of Mars Observer as a precursor for subsequent missions for Mars should be explicitly added to the list of high level objectives for the mission."

3. EVALUATION OF MARS OBSERVER SCIENCE OBJECTIVES

Introduction

We begin this section with two comments on the priority-ranked COMPLEX science objectives for Mars listed in Section 1. The first refers to the top priority among these objectives, the intensive study of local areas. The discussion of this primary objective in the 1978 report and the quantitative specifications given there for the types and precision of measurements required to satisfy it point unambiguously to in situ investigations on the surface of the planet and to sample return. The objective can be implemented only in this way. However, we note that a decade later, in 1988, the expected sensitivity and spatial and spectral resolution of several types of instruments represented on the Mars Observer payload are such that certain orbital measurements are capable of providing information on a local (kilometer or subkilometer) surface scale that bears on some aspects of this objective.

A similar point can be made with respect to the lowest priority objective in the 1978 report, the global chemical and physical characterization of the martian surface. Since this task was included as a primary science objective, the committee at that time explicitly recognized the importance of characterizing whole-planet, major regional (e.g., ancient cratered terrain, polar caps, and Tharsis plateau), and intermediate-scale (e.g., Valles Marineris and Olympus Mons) features, as distinguished from information at the local (few kilometer) scale. However, only GRS determination of whole-planet and major unit chemical composition at low spatial resolution from orbit is called out specifically in the 1978 statement of measurement requirements. One perceived reason for the lack of specificity on the kinds of instruments and measurements required to address this objective is that the committee at that time had only rudimentary (by present standards) Earth-based spectral data and the Apollo x-ray and gamma-ray orbital experiments (and the difficulties in interpreting some of these results) at hand as direct experience. It could not anticipate the degree of technological advance that the next decade would bring to the spatial and spectral measurement capabilities of various types of remote sensing instruments--a particularly important consideration for Mars, with its chemical and physical diversity at regional and intermediate scales. The committee view of this objective from a 1978 perspective thus reflects in part its perception of technological constraints, now less serious although certainly not absent, on acquisition and interpretation of useful data at these scales from orbit.

Evaluation

We now consider, in the context of the central scientific objectives for Mars exploration established and priority-ranked by COMPLEX as given above, the specific science objectives and measurement capabilities of the Mars Observer instruments, and comment on the implementation of each COMPLEX objective by one or more of the stated aims of the MO investigations.

1. Intensive investigation of local areas. The spectral detection capabilities and kilometer-scale surface resolutions of VIMS (~650 m) and TES (~3 km) enable some studies of mineralogy, volatile content, and physical properties of local areas that relate to objectives 1(a) and 1(c). Interpretation of these kilometer-scale spectra is enhanced by the regional-scale compositional information from GRS. Combination of these data with high-resolution imaging by MOC and radar-radiometer observations of local topography and small-scale physical properties by RAR yields a data set that addresses the question of the mineralogical, chemical, and physical nature of local areas on the martian surface. This can provide regional and global context for the mandatory detailed studies carried out later by surface instruments and sample return.

As pointed out at the end of Section 2, high-resolution MOC characterization of the small-scale geological context, landing hazards, and rover trafficability at potential landing sites is essential if Mars Observer is to fulfill a meaningful precursor role for the future MRSR missions that are mandatory for enabling the premier COMPLEX requirement for in situ surface studies and sample return. Other MO measurements relevant to assessment of safety and mobility include TES and RAR characterization of the thermophysical, topographic, and physical nature of the surface on a size scale of a few square kilometers. Such measurements are pertinent to the assessment of block distributions, local slopes, and small-scale physical properties of the surface materials. We include in this category near-surface images from Soviet balloons, if implemented by installation of a relay antenna on MO (or if otherwise available).

2. Structure and general circulation of the atmosphere. This is the highest priority COMPLEX objective that can be substantively addressed by an orbital mission, and as such can be considered the premier objective for MO. The synergistic involvement of almost its entire instrument payload in atmosphere-related studies is fully responsive to the objective and to the types and accuracy of measurement needed to fulfill it, with the single exception of those requirements that can be implemented only by a network of ground-based, meteorological-climatological stations.

The central and dedicated atmospheric instrument is PMIRR. The totality of measurements it provides in quantitatively addressing this objective is unique to the mission. Comparable overall information on thermal structure, water vapor distribution, dust loading, condensates, and diurnal variations cannot be obtained from other experiments that also have some atmospheric objectives (TES, RS, MOC, RAR, GRS, and VIMS). The measurements to be carried out by PMIRR satisfy or exceed the relevant requirements specified by COMPLEX for this next phase of martian exploration.

As responsive as PMIRR itself is to the requirements, however, it is certainly not alone in contributing substantially to the objective. Other instruments play significant roles, both as backups to some (but not all) of the PMIRR capabilities and as providers of unique and relevant ancillary data. TES in particular is noteworthy in this respect: its instrumental objectives include IR spectral analysis of cloud composition and the composition, size distribution, and abundance of airborne dust; mapping of surface temperature pertinent to volatile transport in the boundary layer; determination of the composition of the seasonal and residual polar caps; and, in an objective shared with PMIRR, measurement of polar energy balance.

The atmospheric objectives of RS are highly synergistic with the PMIRR-TES combination: very high vertical resolution profiling of pressure and temperature, particularly in the boundary layer, thermal effects of atmospheric dust loading, and other short-term and seasonal variations in atmospheric structure. Although RS measurements can be made only at occultation locations, these both cover the range from 80°N to

80°S and are concentrated in the climatologically interesting polar latitudes over most of a martian year. It is interesting to consider the possibility that high-resolution (perhaps ~10 m) RS profiles of the boundary layer could detect effects of absorption and release of latent heat accompanying frost deposition and evaporation.

MOC contributes characterization of atmospheric dynamics at widely different scales ranging from the near-surface boundary layer to regional and global weather patterns. Imaging provides inputs and constraints for global climate modeling, including daily cloud formation, wind velocities, condensate transport and precipitation, dust storm incidence and evolution, and seasonal changes as reflected by variations in both transport of visible atmospheric particulates and in aeolian landforms at various scales.

Knowledge of global topography at moderate spatial (~100 km) and vertical (~100 to 200 m) resolution is an essential boundary condition for models of global atmospheric circulation. Altimetric data of this quality could be provided easily by RAR (and by any of the descope options with the possible exception of PV--see Section 4). Mechanical and thermal influences of topography on regional or intermediate-scale atmospheric dynamics (e.g., circumpolar circulation, slope-driven (katabatic) winds, topographically induced waves, dust storm generation) impose more stringent requirements, at the 10 km horizontal and 100 m vertical level. Existing analyses of wind-streak patterns on Viking images provide strong motivation for such local meteorological modeling; the necessary topographic data could be supplied by RAR (and some of the descope options).

Several instruments provide, in combination, a unique and significant data set on the distribution and abundance of volatiles on the surface, and thus on sources and sinks of atmospheric volatiles. Measurements by GRS of near-surface hydrogen provide limits on the water content of the upper regolith, significant for the past history of water distribution as well as its seasonal and longer-term exchange with the atmosphere. VIMS can determine the content of water ice at the very surface of the seasonal carbon dioxide cap as a constraint on the seasonal water cycle. Measures of polar cap energy balance and the seasonal pressure cycle (PMIRR, TES, RS), combined with GRS estimates of seasonal polar cap thicknesses, constrain in a unique way the condensation and sublimation cycle of carbon dioxide. All these considerations are important in understanding the present-day seasonal behavior of surface and atmospheric volatiles, and the long-term history of the climate.

It is clear that there are particularly effective and synergistic associations of PMIRR measurements with those of TES, RS, and MOC, and that integration of these with observations by GRS and VIMS further contribute to the overall area of atmospheric studies. Modeling of the drivers and effects of atmospheric circulation at various scales will advance significantly if currently absent topographic data are provided by RAR, or by some appropriate alternative altimeter or other technique.

3. Structure and dynamics of the interior. This objective is effectively addressed at whole-planet, regional, intermediate, and local (~5 to 10 km) scales by the present RAR instrument through its precise measurements of surface topographic expressions of interior structure and dynamics: regional slopes relating to lithospheric flexure, vertical dimensions of large-scale geologic features, modeling of topographic effects on the gravity field to reveal residual gravitational anomalies related to isostasy, density contrasts, and the like.

The primary contribution of RAR to investigation of interior structure and dynamics is its use in conjunction with gravity data. In the simplest view, regional strength of the gravity field is the sum of contributions from surface topography and interior density anomalies. In order to study the latter, the effects of the former must be removed at a level that does not provide an error source exceeding the basic resolution and accuracy of the observed gravity signal. The accuracy of the gravity data will be about 1 mgal ($=10^{-3}$ cm s^{-2}), and the best resolution is typically taken to be about that of the spacecraft altitude, which for MO is about 350 km. The requirement levied on topographic knowledge so it is not a driving error source depends, in an interrelated way, on both vertical accuracy and horizontal resolution. Typically, individual observations of topography would be averaged over a gravity resolution element or cell, here 350 km on a side. Obtaining a good estimate of the average elevation in a resolution element depends on both the actual topographic variability in the cell and uncertainty in individual measurements. Thus, a large number of individual samples is desirable to reduce the standard deviation of the mean datum; this translates into a horizontal resolution or footprint size. RAR as currently specified meets all requirements imposed by the gravity data and enables detailed topographic studies that in addition relate to a number of the other principal science objectives discussed in this section of the report.

Characterization of the intrinsic planetary magnetic field by MAG bears on the objective in important ways, although this investigation was considered by COMPLEX to be a separate primary science objective and is discussed as such below. If the presence or absence of an intrinsic field is confirmed by MAG, it would provide a significant constraint on models of the planetary core and the global thermal evolution of the planet.

While not specifically noted in Section 2 as an RS topographic objective, radio occultations at spacecraft immersion and emersion will yield measures of planetary radii relative to center of mass (with some topographic ambiguity) with an accuracy of perhaps ~100 m, at some 7000 limb locations spanning 80°N to 80°S in the nominal mission plan but, as noted above, concentrated at polar latitudes. In areas of moderately flat terrain, these measurements would provide valuable absolute tiepoints for any topographic model based on photogrammetric analysis of MOC images or on surface pressure variations. In the absence of any direct altimetric data from MO, the RS occultation data should permit the systematic errors in the present martian topographic model to be reduced to less than or equal to 1 km at all latitudes.

Stereophotogrammetric analysis of MOC images theoretically can provide topographic data pertinent to this objective. This issue is considered separately in Section 4. In addition to this possible application, high-resolution MOC imaging may reveal young or perhaps even contemporary volcanic (e.g., eruption plumes, pristine lava surfaces, and hydrothermal venting) or tectonic (e.g., faulting) activity, thereby providing evidence from surface expressions that bears on the past or current thermal state and stress configuration of the planetary interior.

This overall objective, as defined by COMPLEX, cannot be fully addressed by orbital data alone; it depends critically on measurement of martian seismicity, which in turn requires deployment of a passive seismic network on the surface. We would extend consideration of future surface geophysical instrumentation to include heat flow probes, although we did not explicitly call for them in the 1978 COMPLEX report. The committee is cognizant of the difficulties involved in accurately determining the geothermal gradient, particularly from temperature sensors remotely and probably shallowly deployed, but we would argue that information on the subsurface thermal regime itself is important even in the absence, initially, of a confident measurement of heat flow from the interior.

4. Nature of the magnetic field; character of the upper atmosphere and its interaction with the solar wind. The magnetic field component of this objective is uniquely addressed by MAG. The low-altitude polar orbit of MO facilitates accurate determination of the intrinsic planetary magnetic field, and measurements by MAG can be expected to substantially illuminate, if not resolve, the long-standing controversy concerning the nature of the field.

We note, however, that the MO orbit is not favorable for direct characterization of the upper atmosphere and its interaction with the solar wind. This second part of the overall objective may be addressed in part by RS determinations of the height, peak plasma density, and small-scale structure of the (daytime) ionosphere (e.g., Voyager radio occultation observations at Jupiter and Saturn revealed linear ionospheric structures apparently aligned with local magnetic fields). But full implementation of this objective must be left to a future aeronomy mission. In the meantime, the combination of the low-altitude MO MAG data with anticipated measurements by the Soviet Phobos mission in high-altitude elliptical orbit should yield substantial advances in understanding the solar wind interaction as well as the intrinsic planetary field.

5. Global chemical and physical characteristics of the surface. The primary objectives of the GRS, TES, and VIMS instruments are to furnish,

on whole-planet, regional, intermediate, and local scales, information about the chemical and mineralogical compositions of materials exposed at the martian surface. These include aeolian deposits as well as regolith, rocks, and bedrock to the extent they are present and not covered by windblown dust to the sampling depths of the techniques (tens to hundreds of microns for TES and VIMS, and tens of centimeters for GRS) within their respective footprints. TES and VIMS aim to identify the principal minerals present in these surfaces at high spatial and spectral resolution over the entire surface of the planet.

The GRS will provide relative and absolute concentrations of long-lived radionuclides, major rock-forming elements, and some trace elements on regional or global scales. GRS data (e.g., K/U, Fe/Mg, Cl, and S) permit first-order assessment of planetary composition, differentiation history, and alteration processes, and additionally support the mineralogical interpretation of spectral signatures from TES and VIMS.

The TES and VIMS instruments provide information on mineralogy that is complementary in significant ways. For example, VIMS uniquely enables the identification of iron in the 2+ and 3+ oxidation states, and TES the identification of silica and plagioclase. Both can potentially identify a range of silicate minerals, alteration products, and carbonates. The latter two are central for assessing the history of martian volatiles and climate, and the confidence of detection afforded by independent, confirming spectral signatures at different wavelengths is therefore very important, particularly since both VIMS and TES work best on pure minerals or simple mixtures. More complex mixtures and a range of grain sizes are certain to complicate interpretations of signals from the natural surface environment. An additional dimension of interpretative aid should derive from TES measurements of day versus night emission spectra; these should help distinguish contributions due to the anticipated ubiquitous aeolian dust from those due to intermixed rocks, and to characterize grain size distributions. The impressive correlation of GRS, TES, and VIMS in addressing this difficult mineralogical aspect of surface characterization reflects the careful thought that went into science instrument selection in this area. This synergy improves even more when one adds the capability of MOC, in its high-resolution mode, to establish a geologic context for the spectral and thermophysical measurements by providing detailed information on the physical characteristics and evolution of their footprint areas.

Physical characterization of the surface will be addressed by MOC, RAR, and again by TES and VIMS at various scales. In each resolution mode MOC provides, at relevant levels of surface detail, unique information about ongoing and past aeolian and sedimentary processes, cratering, channel formation, eruptive and erosional styles and rates, and local to regional geologic evolution in general. MOC will be particularly important in evaluating past and ongoing geologic processes contributing to spectral signatures from TES and VIMS (for example, a region of high thermal inertia and characteristic mafic spectral signature could variously be interpreted as a lava flow, crater-excavated debris, or wind-sorted deposit).

RAR will establish the basic local to planet-wide characteristics of martian topography as they apply to surface geological processes at these scales. Of particular importance in regional and intermediate-scale investigations are the statistical distributions of elevations (hypsometry) and the topographic nature of regional geologic provinces (e.g., the Global Dichotomy, the Tharsis and Elysium volcanic provinces, and the Hellas Basin). We note that any of the altimeter options under consideration, discussed in the following section of this report, will acquire data of sufficient accuracy to carry out these large-scale topographic investigations.

VIMS data are relevant to determination of single particle albedos, the microstructure, and other photometric properties of the uppermost surface, and TES data, as noted above, to thermophysical properties, particle size and degree of bonding, and rock abundance, both at local scales of resolution. In this context, microwave radiometry by the currently designed RAR or by the alternative Pioneer Venus (PV) instrument (see Section 4) would provide useful information on the electrical properties, porosity, and bulk density of the upper few tens of centimeters. The combination of brightness temperature at 2.2 cm, IR determination of surface temperature by TES, and direct RAR measurement of radar reflectivity should enable extraction of porosity, sub-centimeter-scale roughness, surface microwave emissivity, and dielectric constant. The dielectric constant is particularly diagnostic of the presence of subsurface liquid water coatings on grains at levels perhaps as low as several percent by volume, or of the presence of metallic phases in the soil. Porosity and bulk density are used in geomorphological studies of mass-wasting and other mechanisms. Estimates of small-scale surface roughness relate to impact and aeolian processing of the regolith and to interpretation of near-IR reflectance and mid-IR emissivity measurements by VIMS and TES, respectively.

4. ASSESSMENT AND IMPLICATIONS OF CANDIDATE INSTRUMENT DESCOPING/DELETION OPTIONS UNDER CONSIDERATION BY NASA

The committee's objective in this section of the report is to assess, in the light of the discussion above, the scientific impact of descoping or deleting specific instruments in the Mars Observer payload. It is first necessary to state that we do not consider this mission, despite its name, to be in accord in any significant fashion with the definition of the Observer mission class as it was originally envisioned by the Solar System Exploration Committee (SSEC) in its report, Planetary Exploration Through the Year 2000 (1983). It has escalated in level of investment, and in the degree of anticipated science return required for commensurability with this investment, very far beyond any possible perception as one of a series of frequently launched, relatively inexpensive, and moderately risky spacecraft aimed toward comparatively narrow sets of scientific objectives. In part this evolution in sophistication, complexity, and cost is due to the unusual heritage of Mars Observer as a combination of two earlier plans for more narrowly focused and separate investigations of water on Mars and of the geochemical nature of its surface. These were later combined into what was then MGCO (Mars Geoscience/Climatology Orbiter), and subsequently MO.

For whatever reasons, Mars Observer has now outgrown all of the original Observer-class parameters. Moreover, it is clear from the recently promulgated OSSA Strategic Plan that with the failure to establish a true Observer line, MO almost surely represents the only mission to Mars by this nation in the coming decade. COMPLEX therefore takes the position that in these circumstances MO cannot be judged by the criteria for science return that would apply to Observer-class missions as initially conceived by the Solar System Exploration Committee. Consequently, the potential surrender of any current mission capability that substantively addresses the primary science objectives established for the exploration of Mars is a matter of great concern to the committee.

Radar Altimeter (RAR)

The evaluations carried out in the preceding section demonstrate that topographic data are required for implementing the COMPLEX science objective 3 relating to the structure and dynamics of the martian interior. They are also needed at various levels of vertical and horizontal resolution to address the modeling of atmospheric circulation (objective 2) and the geologic structure and physical nature of the surface (objective 5). Moreover, such data can contribute to assessments of sites and hazards relevant to future landing and intensive studies of local areas (objective 1). Knowledge of topography is thus essential or strongly coupled to fulfillment of high priority science objectives, and the committee considers the generation of global topographic information, by some means, at a level of accuracy sufficient to substantively address objective 3, to be a central component of mission capability.

Even though all of the potential actions presented to us for reduction in mission scope involve deletion of RAR in its present design configuration, we are informed that various instrumental options for preserving topographic capability on Mars Observer exist and are under study. These range from possible alternative altimeters that measure surface topography directly with a variety of vertical and horizontal resolutions, to stereophotogrammetric recovery of topographic information from MOC images. The committee was greatly assisted in discussions of these alternatives and their abilities to address the COMPLEX science objectives by a comprehensive memorandum on this subject, dated May 23, 1988, from M. Carr to G. Briggs. In the following we summarize our perceptions of the options that at this time appear to be under consideration.

Figure 1 shows estimates of horizontal and vertical resolutions needed for useful topographic data relevant to a number of geological, geophysical, and atmospheric processes, compared to the performances of six different methods for acquiring the data. Given the requirement that topographic errors do not drive the uncertainties in gravity modeling, the committee's assessment of the required level of topographic definition is depicted by the dashed curve. It is seen that MORAR (RAR), S-MORAR (Simplified RAR), SIR-C (Shuttle Imaging Radar-C derivative), and MOLA (an MO version of the laser altimeter under development for the Lunar Geoscience Observer mission) all meet this requirement, although it was felt that MOLA, with its small, undersampled footprint, could be subject to some additional error through cross-track aliasing in determining meaningful average elevations unless repeated measurements are made. The PV (Pioneer Venus) altimeter falls below the cutoff for requisite performance. (We note, however, that even its data would greatly improve our knowledge of martian topography, and would enable geophysical analyses of the type and accuracy that have been carried out for Venus.) There is a degradation of information in going from MOLA to MORAR to S-MORAR to SIR-C. The first three of these instruments provide horizontal resolution no worse than 10 km and vertical resolution no worse than a few tens of meters, and as shown in Figure 1 are capable of addressing a variety of important geomorphological and regional geophysical questions. MOLA, with its 2.7 km x 360 m footprint size and <1 m vertical resolution, could provide detailed profiles yielding information on very small scale features and subtle surface slopes and slope changes. As noted above, however, spacecraft pointing uncertainties equivalent to the order of 1-km displacement on the surface could complicate interpretation of such data unless corrected in some unambiguous way.

The committee is intrigued by, but uncertain about, the potential for acquiring topographic information via digital stereophotogrammetric (DSP) methods applied to MOC images. Our estimate of the possible accuracy range of topographic data obtained in this manner is shown in Figure 1. In the most optimistic view, DSP would yield results at the desired level for gravity modeling. A more realistic view might be performance at about the level of PV, and a conservative assessment would suggest that DSP is completely inadequate for geophysics. We emphasize that quantitative assessment of the ability of DSP to provide useful topographic information from the push-broom MOC camera images has not been made. Such an evaluation, and affirmation of its capability at the requisite levels of accuracy, is absolutely required before DSP can be regarded as a credible alternative source of such data.

Camera (MOC)

It is clear from Section 3 that the camera images support COMPLEX objectives 1, 2, 3, and 5 in various ways. Deletion of imaging capability would have significant consequences for the component of objective 2 that relates to atmospheric circulation, specifically loss of ability to relate

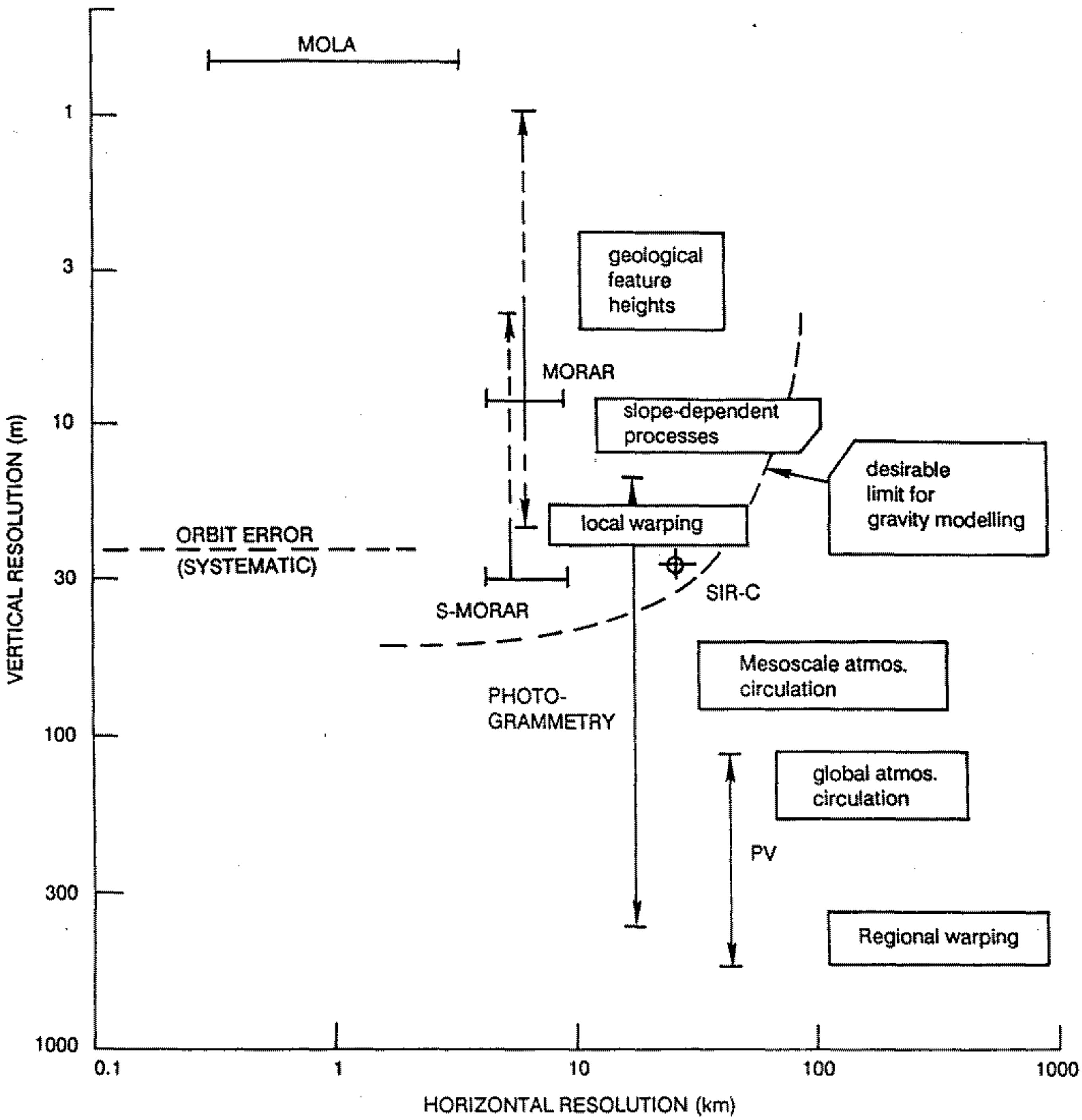

FIGURE 1: Science contraints on MO altimetry and predicted performance of various proposed instruments (S-MORAR = simplified MORAR).

NOTE: Nominal MORAR/S-MORAR points correspond to range resolution/sample. Higher resolutions (1 m/4 m) result from averaging to 2 points/s.

time-varying atmospheric phenomena characterized by other instruments to visible expressions of atmospheric dynamics and thus to modeling of atmospheric circulation on local to global scales. Potential loss of association of MOC images with TES and VIMS measurements in objective 5 is also significant in that it would remove the possibility of placing these spectral and physical observations in detailed geological context, as revealed by MOC at high optical resolution over surface areas commensurate with their footprints. This would seem to be particularly valuable in addressing interpretive ambiguities due to effects of surface and surface-atmospheric processes such as wind blown dust deposition, wind scour, and the like.

Although its scientific utility in high-resolution, local-scale surface characterization is unquestioned, MOC acquires a priority of a quite different order with respect to objective 1, the intensive study of local areas, if the precursor role of MO for a future rover sample return mission is considered to be a high-level mission objective--a position that COMPLEX endorses in view of the primary scientific priority assigned to objective 1 in the exploration strategy for Mars. MOC is clearly the most important instrument on MO in implementing such an objective. The usefulness of the camera can be assessed in a similar fashion with regard to objective 3: it is a desirable supporting instrument for identification of small-scale surface features that may bear on the past or current state and dynamics of the interior, but it is critical *if* MOC images are demonstrated to be suitable for recovery of accurate topographic data by stereophotogrammetry, *and if* no more direct and proven capability for providing topographic information is present on the mission. However, we reiterate here the caution about this technique expressed immediately above.

Thermal Emission Spectrometer (TES) and Visual and Infrared Mapping Spectrometer (VIMS)

We group these two spectral instruments together for this part of our assessment, specifically to emphasize the point made in Section 3 about their high degrees of complementarity in addressing the part of objective 5 that concerns the global chemical and mineralogical characterization of the martian surface. The complementary capabilities of TES and VIMS should not be taken to imply a high degree of redundancy in their measurements. Deletion of either would force a very difficult choice between measurement of major and fundamental diagnostics of mineralogical character, for example iron oxidation state and silicate structure, and would reduce confidence in detection of minerals that both instruments can observe but at different wavelengths--including the sulfates and carbonates that are so important in understanding martian volatile and climate history.

Elimination of either TES or VIMS would result in deletion of additional instrumental capabilities that apply individually to a wide range of important objectives. Removal of VIMS would mean loss of its power to generate in a short period of time a high-resolution (~650 m), broad-swath (40 km) spectral map of the planet, as well as its unique abilities to determine the presence of OH-, diagnostic for clay minerals, and to identify surface water ice. Loss of TES would remove all capability to identify feldspar and quartz, two major rock-forming minerals, and delete the unduplicated ability of this instrument to address the mineralogical nature and particle size distribution of atmospheric dust (objective 2) and the thermophysical properties of surface materials.

We have not been asked to address an option that involves removal of TES and VIMS. However, since both are on the candidate descoping list, we consider it necessary to point out that deletion of both spectral instruments would effectively strip the mission of all mineralogical and rock identification content. The committee would strongly recommend against such action were it to be proposed.

Descoping-Deletion Combinations

It is our intent here to note particular scientific hazards, above and beyond the more general assessments of science loss detailed in Section 3, that could attend the exercise of reducing the MO payload by descoping one and removing another of these four instruments. It is our understanding that only one of them, RAR, is currently being considered for descoping rather than deletion, and that this reflects an agency decision, subject to a cost cap now set at $10M, to retain competent altimetric capability on the mission. If this cost cap later proves to be unrealistic, a scenario involving the RAR-MOC option could easily be envisioned in which MOC is removed now and the alternative altimeter deleted at some later time because of cost escalation. Such a development would completely compromise primary, high-priority science objectives in that it would strip the mission of both direct measure of topography and any potential for recovering sufficiently accurate topographic data from stereophotogrammetric analysis of MOC images.

We have used the RAR-MOC combination to point out a specific hazard, but it also illustrates a more general concern: that later cost considerations will threaten even the alternative altimeter, thereby causing the mission to suffer the loss of two major instruments. If this kind of creeping attrition of the payload were to occur, any of the options combining a descoped (and ultimately deleted) altimeter with elimination of MOC or TES or VIMS would represent too severe a loss of overall capability in the context of our perception of this mission and the appropriate data return from it.

In what follows the committee assumes that the agency commitment to a competent alternative altimeter is firm, and it will fly. In this case, while greatly regretting the loss of unique and important measurement capabilities that will attend the exercise of any one of the three options, we judge that Mars Observer would still be responsive to COMPLEX priorities, marginally within our expectations for data return from a mission with this scale of investment, and thus still scientifically viable. But on the specific matter of choosing among the RAR-MOC, RAR-TES, and RAR-VIMS options, COMPLEX can do no more than set out, as we have above, our perception of the scientific criteria that in our view must guide the final decision.

Other Instruments

COMPLEX has not extended the matrix of possible reduction options beyond those we were specifically requested to assess. In Section 3, however, we have evaluated all eight instruments uniformly in the context of their roles in addressing science objectives. Had the committee perceived weaknesses in objectives or measurement capabilities incommensurate with the inclusion of one or more of them on a mission so financially beleaguered, we would have noted them.

5. IMPLICATIONS OF DELAY IN MARS OBSERVER LAUNCH UNTIL 1994

The option of delaying the MO launch until 1994 was raised by L. Fisk of NASA-OSSA at the Mars Observer Project Review on May 31, 1988, and discussed by the attendees. Little if any support for it was expressed at that time. The committee has additionally considered several anticipated scientific (and, in this case, programmatic) consequences of further postponing the launch, and is unanimous in believing that this response to current financial difficulties would be extraordinarily unwise. Delay in launch would mean still further delays not only in data return from MO (to more than 15 years after the end of the Viking mission) but also, in our opinion, in the development of a comprehensive agency focus on planning and implementing such scientifically mandatory downstream missions as Mars Rover Sample Return. The MO mission itself would be likely to suffer a purely scientific penalty of some magnitude. A 1994 launch leads to timing of spacecraft arrival at Mars almost coincident with initiation of the anticipated global dust storm season. This would probably preclude, among other observations, prestorm surface mapping and thus the opportunity for comparative prestorm and poststorm examination of surface response to the storm environment.

Moreover, the implicit assumption of this option, that financial problems are eased by schedule slip, is demonstrably unsound on any but the shortest time scales. The mission penalties that accrue from the false economies of near-term savings are cogently illustrated by the situation at this moment for Mars Observer itself, under financial threat of reduction in scientific scope 2 years after cost-driven imposition of launch delay from 1990 to 1992. It is all too likely that the consequences to science of a further postponement would be no better, and could well be worse in view of probable funding reductions and personnel attrition, with an accompanying loss of competence and experience in instrument development teams. These and other consequences of delays in mission schedule are addressed in detail in the 1986 NASA Space and Earth Science Advisory Committee report, The Crisis in Space and Earth Science. We conclude that neither the MO science objectives, probable instrument capabilities and potential data return, nor planning and instrument development for post-MO exploration of Mars, would be well served by a further launch delay.

6. CONCLUSIONS

The committee offers here its summary opinion of the Mars Observer mission as currently designed, and an attendant conclusion and recommendation, which follow from the science assessment presented above. As we have pointed out, the Mars Observer mission has evolved from the Observer class as originally conceived to a mission of significantly broader scale with much higher investment and more extensive goals. Judged in this context, its payload is well chosen. The technologically advanced measurement capabilities of its instruments, individually and in combination, address essential elements of all major scientific objectives set forth by COMPLEX for exploration of Mars that are achievable in a low-altitude orbital mission. Therefore science return from Mars Observer as currently configured is appropriate to the level of investment in the mission, but this return is highly sensitive to the strength of the science instrument complement and will diminish to incommensurate levels much more rapidly than money can be saved by levying the penalties of mission inflation on the payload. The current mission is also capable of serving an important additional role at this time of developing international interest in the scientific investigation of Mars, as a precursor for landing, automated exploration of the surface, and the return of samples for laboratory study. From these considerations and those discussed above in Section 5, *the committee concludes that Mars Observer in its present configuration is ambitious, sophisticated, and broadly oriented toward major scientific goals. It is also expensive, but with appropriate support for its precursor role we find it commensurately responsive to all objectives of martian exploration established by COMPLEX. We must therefore recommend (1) that every effort be made to preserve intact (with the possible exception of a redesigned or alternative radar altimeter) the science instrument payload of Mars Observer as originally selected; (2) that the OSSA give due attention to the value of a dual role for this mission, as an orbital science mission and a precursor mission for future rover deployment and sample return; and (3) that the project adhere to its present schedule, leading to launch in 1992.*

The committee further concludes that missions that are in accord with the SSEC Observer-class criteria of frequent launch, modest scale, high inheritance, and low cost are essential components of a timely, efficient, and comprehensive program of inner solar system exploration. The SSEC anticipated that Mars Observer would be the first product of a level-of-effort Planetary Observer program. It is not, but COMPLEX continues to endorse the concept of such a program and strongly urges that it be established promptly and conducted within the guidelines appropriate to it.

On the difficult issue of MO payload instrument deletion, the committee here restates and amplifies the conclusion reached in Section 4. A reduction in the scientific scope of Mars Observer, imposed on the project as a last-choice response to the current financial crisis and implemented along the lines currently under consideration by the agency--as reflected in their specific options for instrument descoping and deletion--would leave the mission, as assessed against the COMPLEX objectives, in a degraded but still scientifically viable state, *provided that the choice among the stated options is made with the most careful attention to the scientific penalties incurred and with full and responsible commitment to minimizing the consequences of these penalties*. COMPLEX has attempted in this report to provide scientific guidance for this choice, should it have to be made.

The committee requests that it be kept fully informed of agency action in this matter. Should further reductions in Mars Observer objectives and/or delay in mission schedule prove, in the opinion of the agency, to be necessary, we would expect to carry out a review of the additional attenuation in data return and to reassess fully the ability of the mission to address in a broad and comprehensive fashion the priority science objectives set out by the Space Science Board for the exploration of Mars.

Sincerely yours,

Robert O. Pepin
Chairman, COMPLEX

cc: Lennard Fisk