STATUS AND FUTURE OF U. S. EXTRATERRESTRIAL MAPPING PROGRAMS

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ABSTRACT: Thus far, surfaces of 14 planets and satellites have been mapped with spacecraft data. Of these bodies, only the Moon and Mars were mapped with images that allow photogrammetric measurement of topographic elevations; the others can be mapped only planimetrically. More than 600 maps of the Moon were published between 1962 and 1974. Since 1972, more than 200 maps of Mars have been published, along with approximately 50 maps of other bodies. Data return from interplanetary spacecraft reached its peak between 1976 and 1980, when the Viking Missions to Mars and the Voyager Missions to the Jovian and Saturnian systems were operating. Another heavy influx of data is expected between 1989 and 1992, when the Galileo Mission to Jupiter, the Venus Radar Mapper Mission, and the Mars Geoscience/ Climatology Orbiter will be active. Meanwhile, the U. S. National Aeronautics and Space Administration (NASA) has given high priority to: completion of the mapping of Mars at 1:2,000,000-scale, with extensive special mapping at larger scales; mapping of the Galilean satellites of Jupiter at 1:5,000,000-scale; and mapping of six of the satellites of Saturn at scales of 1:2,000,000 and 1:5,000,000. A very large program for mapping Venus will begin in 1989, simultaneously with a program for compiling higher resolution maps of the Galilean satellites. Programs for mapping two or three of the satellites of Uranus, and Triton, the largest satellite of Neptune, will begin in 1986 and 1989, respectively. These two programs will be small, however, because of Voyager 2's expected sparse return of imaging data.

INTRODUCTION

NASA has recently received a plan for extraterrestrial mapping during the next ten years (Planetary Cartography Working Group, 1984). The significant parts of that plan are presented here, along with an outline of the current status of planetary mapping. A previous report (Batson, 1980) contains details of planetary mapping programs, techniques, and history that are not duplicated in this paper.

During the two decades prior to 1980, the United States program for planetary exploration consisted of large, complex, and expensive programs that utilized spacecraft, instrumentation, and support systems individually designed for each mission. Although these missions were spectacularly successful in producing large quantities of scientific data, their cost and complexity was becoming difficult to justify, both politically and economically. NASA's Solar System Exploration Committee (SSEC) developed and published a plan (Solar System Exploration Committee, 1983) for continuing the exploration of the solar system with modular spacecraft and support systems that, once designed, could be used for a variety of missions with relatively minor modifications. In accordance with this plan, exploration of the Solar System by the U. S. is likely to continue with frequent small missions, rather than sporadic large ones. It is inevitable, however, that implementing a policy of this kind will include some apparent inconsistencies: for a variety of programmatic and technical reasons, two long-planned missions with large cartographic data return are scheduled to take place within the same two-year period. In 1988, the Venus Radar Mapper and the Galileo Mission to the Jovian system will end nearly a decade of relative inactivity in the U. S. program of planetary exploration.

The relatively low level of spaceflight activity has allowed cartographic consolidation of large data sets, particularly for Mars. More than 50,000 images of Mars were produced prior to 1980 by Viking alone. These images, together with Mariner pictures of Mars and Mercury, Voyager pictures of the satellites in the Jovian and Saturnian systems, and Apollo and Lunar Orbiter pictures of the Moon, have been used to compile more than 1000 maps of 14 planets and satellites in our Solar System. This work is not yet complete. Many of the highest resolution pictures of Mars were taken late in the Viking mission, and have only recently undergone the basic processing required for cartographic compilations. They contain the key to fundamental geologic questions that cannot be addressed until they are incorporated into high-resolution maps and photomosaics.

The Voyager 1 and 2 data provide a tantalizing glimpse of the satellites in the Jovian and Saturnian systems. Comprehensive investigations, however, must await data from future missions such as Galileo and others not yet designed or approved. The resolution of the best of the Voyager pictures (1 to 20 or more kilometers per pixel) is comparable to that of the Mariner 9 pictures of Mars, but their areal coverage is not nearly as complete. The maps that have been or are being made with Voyager pictures provide a graphic delineation of the status of the Jovian data set, because the amount of surface detail mapped varies with the resolution of the available images.

In the past, we have been able to maintain the planetary cartography program at a uniform level in spite of periods of furious data-gathering activity followed by relatively quiescent times (figure 1). It is not clear that this level can be maintained during the 1990's, however, when the Venus Radar Mapper is expected to return radar images in volume at least equivalent to that received from Viking, when Galileo returns several thousand multispectral images of four planet-size satellites, when the Mars Geochemical/Climatological Orbiter (MGCO) returns radar elevations at 10-m intervals over most of Mars, and when a Mars roving vehicle may return high-resolution images and other data along traverse routes several kilometers in extent. These problems will dominate cartographic planning toward the end of the coming ten-year period (figure 2).

PLANETARY MAP SERIES

Planetary maps are compiled in a variety of forms and scales, based on the needs of the user community and the availability of resources. The basic planetary map types are: 1) controlled photomosaics; 2) airbrushed shaded relief, which may also show albedo markings; and 3) topographic contour maps. Scale series include: 1)synoptic maps, which show an entire planet or satellite on no more than three sheets; 2) quadrangle maps, for systematic planetwide mapping at scales of 1:1,000,000 to 1:5,000,000; and 3) special-area maps, selected on the basis of their scientific interest, and which generally cover only a few small areas on a planet at high resolution.

The actual scales selected for various map series depend on the size of the planet or satellite being mapped. The intent is to display a complete view of the object on the fewest possible map sheets (table 1). Venus or Earth cannot be conveniently mapped on a single sheet at scales much larger than 1:50,000,000, whereas the equator of Mimas (a satellite of Saturn) is only 62 cm long on a Mercator map with a scale of 1:2,000,000.

Table 1. Planetary map series. Figures indicate total number of map sheets or quadrangles required for a single version of a complete series. Several versions or editions are often published. Conversely, only a small selection of some series of quadrangles is compiled, based on scientific requirements and on data and resource availability. For example, only 44 of a possible 144 1:1,000,000-scale quadrangles, and 232 of a possible 1152 1:250,000-scale quadrangles of the Moon were compiled. Similarly, there are no plans to compile more than two or three hundred of the 1:500,000-scale quadrangles of Mars.

					JOVIAN SYSTEM				SATURNIAN SYSTEM					
	MERCURY	VENUS	MOON	MARS	Io	Europa	Ganymede	Callisto	Mimas	Enceladus	Tethys	Dione	Rhea	Iapetus
Synoptic maps														
1:50,000,000	-	1	-	-	-	-	-	-	-	-	-	-	-	-
1:25,000,000	-	3	-	1	1	1	1	1	-	-	-	-	-	-
1:15,000,000	1	8	-	3	1	1	3	3	-	-	-	-	1	1
1:10,000,000	-	-	1	-	-	-	-	-	-	-	1	1	-	-
1:5,000,000	-	-	3	-	3	3	-	-	-	-	-	-	1	1
1:2,000,000	-	-	-	-	-	-	-	-	1	1	-	-	-	-
Quadrangle maps														
1:5,000,000	15	62	-	30	-	-	15	15	-	-	-	-	-	-
1:2,000,000	-	-	-	140	-	-	-	-	-	-	-	-	-	-
1:1,000,000	-	-	144	-	-	-	-	-	-	-	-	-	-	-
1:500,000	-	-	-	1964	-	-	-	-	-	-	-	-	-	-
1:250,000	-	-	1152	-	-	-	-	-	-	-	-	-	-	-

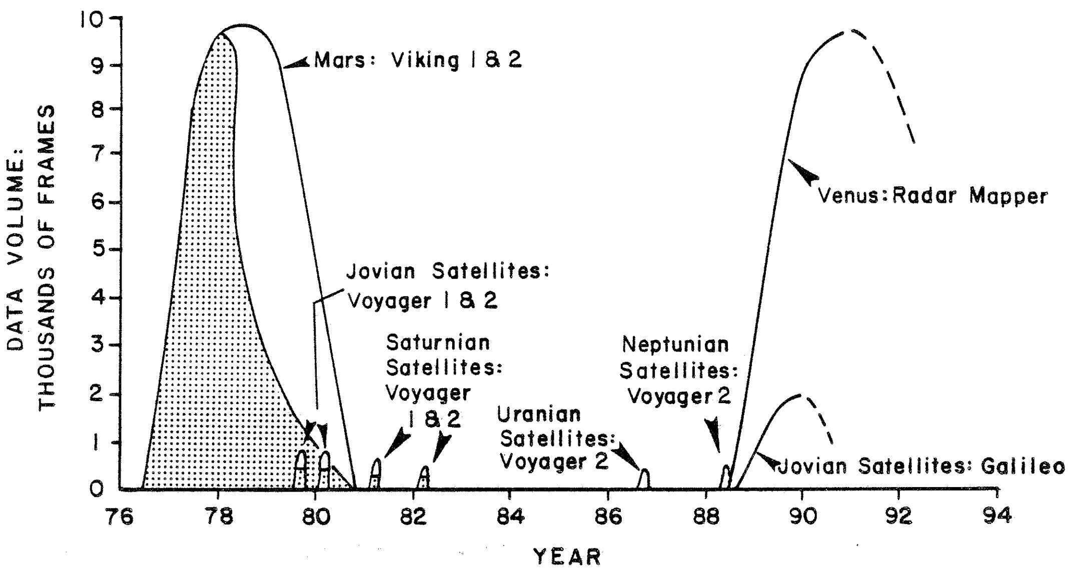

Figure 1. Volume of images returned by U.S. interplanetary spacecraft, actual and anticipated, through 1994. Hatched areas indicate the percentage of the datasets utilized in cartographic compilations to date. Voyager data for the planets Jupiter and Saturn are not represented because those bodies have no solid surfaces and cannot be mapped in the traditional sense. A much higher proportion of effort must be devoted to cartographic processing of the Voyager data than to the Viking data to produce maps with similar characteristics.

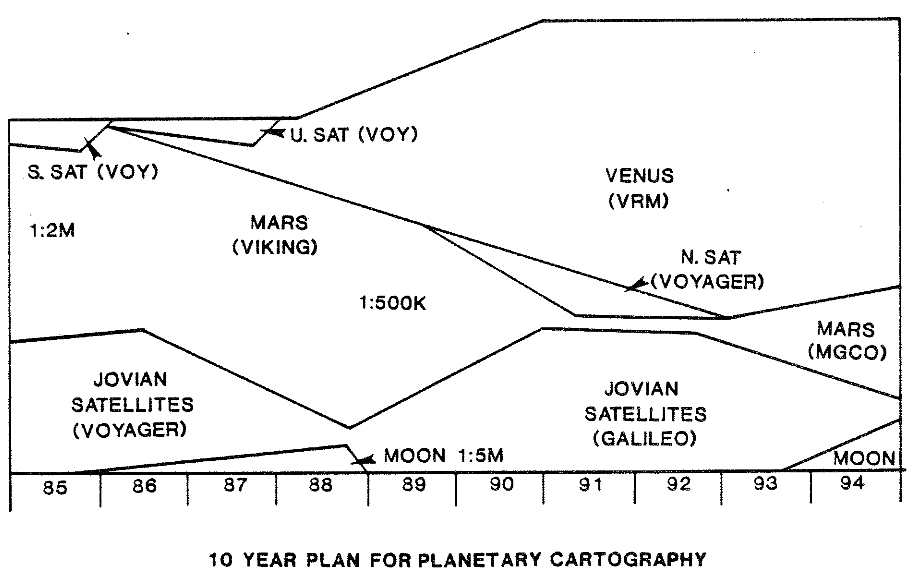

Figure 2. Level of effort to be devoted to extraterrestrial mapping during the decade 1984-1994.

Systematic quadrangle mapping is done at scales of 1:2,000,000 to 1:5,000,000, depending on user interest and source data resolution. Special area maps are often made at the largest scale that can be supported by the resolution of the source data.

Controlled photomosaics are the most common form of planetary map because spacecraft images are the primary source of available data. These images are usually digital, amenable to a variety of geometric and radiometric computer processing methods. Because of the way the pictures are taken, they are subject to wide variation in resolution, tilt, and conditions of surface illumination. Pictures taken from orbiting spacecraft in a systematic fashion, with low tilt angles, can be compiled into controlled photomosaics. Most rectified spacecraft images can be considered orthophotos, because topographic parallax is very small compared to image resolution. A few small sets of spacecraft pictures have resolutions and geometric configurations that allow compilation of contour maps by stereophotogrammetry.

The airbrush is used to compile maps of surfaces surfaces that are not adequately characterized by spacecraft images. Such is the case where images are taken with a wide range of resolution and viewing geometry and under various conditions of surface illumination and obscuration by clouds or haze. Persons capable of making useful airbrush maps are very rare, however, because the field is highly specialized and many years of training in photointerpretation and landform portrayal are required. The technique is therefore used only where no other method is practical. Where image resolution allows, the portrayal of landforms with the airbrush is separated from the depiction of albedo patterns, and separate maps are published showing relief only and relief with albedo overprints. The latter present a more "pictorial" view that may more closely resemble existing and future photographs. The former are preferable when illustrating geologic structure and stratigraphy.

Topographic contour maps are compiled where adequate data are available. The contour lines are often overprinted on either airbrushed maps or controlled photomosaics, or they may be published as "stand-alone" line maps as well.

CURRENT STATUS OF PLANETARY MAPPING

More than 1000 maps of planets and satellites have been published since 1962. More than 800 of these are lunar maps, and most of the rest are maps of Mars. Only a handful of maps of other planets and satellites have been made. Tables 2 and 3 show the status of map-sheet compilation and publication.

Table 2. Maps published as of May, 1984. Maps of Io, Europa, Ganymede, and Callisto are included under the heading "J. SAT.", and maps of Mimas, Enceladus, Dione, Tethys, Rhea, and Iapetus are included under the heading "S. SAT.".

SERIES	MERCURY	VENUS	MOON	MARS	J.SAT.	S.SAT.	TOTAL
Synoptic maps							
photomosaics	1	-	-	-	-	-	1
airbrush	2	-	9	7	4	10	32
topographic	-	1	-	1	-	-	2
Totals	**3**	**1**	**9**	**8**	**-**	**-**	**35**
Quadrangle maps							
photomosaics	-	-	219	107	-	-	326
airbrush	9	-	75	32	-	-	116
topographic	-	-	273	14	-	-	287
Totals	**9**	**-**	**567**	**153**	**-**	**-**	**729**
Special formats							
Totals	**1**	**-**	**259**	**21**	**3**	**-**	**284**
TOTALS	**13**	**1**	**835**	**182**	**7**	**10**	**1048**

Table 3. Map sheets currently in compilation or in press. Maps of Io, Europa, Ganymede, and Callisto are included under the heading "J. SAT.", and maps of Mimas, Enceladus, Dione, Tethys, Rhea, and Iapetus are included under the heading "S. SAT.".

SERIES	MERCURY	VENUS	MOON	MARS	J.SAT.	S.SAT.	TOTAL
Synoptic maps							
photomosaics	-	-	-	-	2	-	2
airbrush	-	-	-	2	2	-	4
topographic	-	2	-	1	-	-	3
Totals	**-**	**2**	**-**	**3**	**4**	**-**	**9**
Quadrangle maps							
photomosaics	-	-	-	83	-	-	83
airbrush	-	-	-	4	13	-	17
topographic	-	-	-	13	-	-	13
Totals	**-**	**-**	**-**	**100**	**13**	**-**	**113**
Special formats							
Totals	**1**	**1**	**1**	**3**	**4**	**6**	**16**
TOTALS	**1**	**3**	**1**	**106**	**21**	**6**	**138**

PLANS FOR PLANETARY CARTOGRAPHY BETWEEN 1984 AND 1994

A set of recommendations for the compilation of planetary maps over the next ten years has been made by NASA's Planetary Cartography Working Group. The group consists of planetary scientists from universities and government agencies, and of cartographers acquainted with the problems and techniques of planetary cartography (Appendix). The recommendations are based on optimum utilization of both existing data and data to be returned from future missions.

Parts of the Viking Orbiter and Voyager 1 and 2 image data sets have not yet been thoroughly exploited for their scientific and cartographic content. The image data set from the Voyager 1 and 2 missions is small, but contains extensive coverage of the four major satellites of Jupiter and six satellites of Saturn. Voyager 2 is expected to return images from the Uranian system in 1986 and from the Neptunian system in 1989.

The Viking orbiter data set for Mars consists of more than 50,000 images. Approximately 23,000 of these have resolutions ranging from 7 to 100 m per pixel. Uncontrolled mosaics of these images have been compiled, but extensive systematic exploitation of their scientific and cartographic potential has only recently begun, with the compilation and publication of several sheets in a new 1:500,000 Mars Transverse Mertcator (MTM) map series. The series was designed to provide a framework for systematic compilation of large scale maps of areas of special scientific interest. No attempt will be made to map all of Mars at 1:500,000-scale.

Table 4 outlines future missions that will support planetary mapping.

Table 4. Planetary missions that will return mapping data during the ten years from 1984 to 1994.

PLANET	MISSION	DATE	EXPECTED DATA
Satellites of Uranus	Voyager 2	1986	High- to medium-resolution images of Miranda and Ariel
Venus	Venus Radar Mapper	1988	High-resolution radar images and altimetry covering about 90% of the surface
Satellites of Jupiter	Galileo	1988	High-resolution images of Callisto, Ganymede, Europa, and Io
Satellites of Neptune	Voyager 2	1989	High- to medium-resolution images of Triton
Mars	Mars Geoscience/ Climatology Orbiter (MGCO)	~1991	Global high-resolution altimetry, geochemical and geophysical data

Resources for extraterrestrial mapping will be allocated as shown in Figure 2. Table 5 shows the numbers and types of map sheets currently planned for completion during the coming decade. The figures are based on maximum possible data return and are probably optimistic. In several cases, they include the same compilation in more than one published format. For example, the synoptic map of Venus will be compiled in preliminary and final versions on eight sheets for each version, at a scale of 1:15,000,000. The same compilations will be published at scales of 1:25,000,000 on three sheets and 1:50,000,000 on a single sheet. Thus, 12 sheets will be published from a single compilation. Preliminary synoptic maps of Venus will be compiled at 1:25,000,000-scale and published at 1:50,000,000-scale on a single sheet and at 1:25,000,000-scale on three sheets. Similarly, many topographic maps will be published both as "stand-alone" contour maps and as maps with contour lines overprinted on either airbrush or photomosaic bases.

Table 5. Approximate number of sheets planned during the ten-year period 1984-1994. Maps of Io, Europa, Ganymede, and Callisto are included under the heading "J. SAT.", and maps of Mimas, Enceladus, Dione, Tethys, Rhea, and Iapetus are included under the heading "S. SAT.". Maps of Ariel and Miranda are included under the heading "U.SAT.", and maps of Triton under the heading "N.SAT."

SERIES	MERCURY	VENUS	MOON	MARS	J.SAT.	S.SAT.	U.SAT.	N.SAT.	TOTALS
Synoptic maps									
mosaics	-	16	-	-	-	2	2	3	23
airbrush	-	16	2	3	18	12	10	7	68
topographic	-	16	-	6	-	-	-	-	22
Totals	-	**48**	**2**	**9**	**18**	**14**	**12**	**10**	**113**
Quadrangle maps									
mosaics	-	62	-	390	214	-	-	15	681
airbrush	-	62	-	30	76	-	-	30	198
topographic	-	124	-	260	-	-	-	-	384
Totals	-	**248**	-	**680**	**290**	-	-	**45**	**1263**
TOTALS	-	**296**	**2**	**689**	**308**	**14**	**12**	**55**	**1392**

APPENDIX: The Planetary Cartography Working Group.

This group of planetary scientists makes up the NASA advisory group for planetary cartography. The chairman and most members are appointed by the Lunar and Planetary Science Institute, Houston, Texas, for three-year terms. The group acts as a clearing house for specific mapping requests by individual planetary scientists, and makes recommendations to NASA regarding planetary mapping priorities and specifications. The group listed below authored the current NASA ten year plan for planetary cartography (PCWG, 1984). The chairman and some of the members have completed their terms, and appointment of replacements is in progress.

Robert G. Strom (Chairman); University of Arizona, Tucson, Arizona

Raymond M. Batson; U. S. Geological Survey, Flagstaff, Arizona

Joseph M. Boyce (Ex-Officio); NASA Headquarters, Washington, D. C.

Merton E. Davies; The Rand Corporation, Santa Monica, California

Frederick J. Doyle; U. S. Geological Survey, Reston, Virginia

Thomas C. Duxbury; Jet Propulsion Laboratory, Pasadena, California

Matthew P. Golombek; Jet Propulsion Laboratory, Pasadena, California

Harold Masursky; U. S. Geological Survey, Flagstaff, Arizona

R. Stephen Saunders; Jet Propulsion Laboratory, Pasadena, California

William L. Sjogren; Jet Propulsion Laboratory, Pasadena, California

James R. Underwood; Kansas State University, Manhatten, Kansas

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