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Planetary Cartography in the Next Decade: Digital Cartography and Emerging Opportunities

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1. SUMMARY OF RECOMMENDATIONS

The planetary maps that are produced today will represent a view of the Solar System for generations to come. The first objective of the planetary cartography program is to produce the most complete and accurate synopsis of the thousands of planetary images obtained thus far in Solar System exploration. These products must support research and future missions; perhaps even more importantly, they must accurately represent the scientific findings of planetary exploration. The document **Planetary Cartography in the Next Decade (1984-1994)** [NASA SP-475] outlines the broad program required to support planetary exploration. The supplement presented here does not alter the basic recommendations published previously. Rather, it emphasizes the utilization of digital techniques and digital data bases to take advantage of recent advances in computer technology.

Recommendations in addition to those in the ten-year plan are as follow:

1. Digital image models should be prepared for as many planetary bodies as can be supported by available data. At present, these include Mars, parts of Mercury, the outer planet satellites, and the Moon.
2. The J2000 reference system should be adopted as the standard for planetary cartography.
3. Digital cartographic data should be produced and widely distributed in standard formats to allow correlations among multiple data sets.
4. Data-processing cartographic work stations should be provided to planetary scientists to utilize digital cartographic data.
5. The 1:5,000,000-scale nearside map of the Moon should be compiled and published.
6. Earth-based radar cartographic data for Mercury should be compiled and combined with existing maps.
7. The techniques required for treating the cartography of irregular objects such as small satellites, asteroids, and comets should be developed.
8. A high priority should be assigned to the acquisition of necessary cartographic data on future planetary missions.

2. INTRODUCTION

In 1984, the Planetary Cartography Working Group completed a study addressing the cartographic needs of planetary scientists for research and for mission planning and execution. The results of this study were published as NASA SP-475 "**Planetary Cartography in the Next Decade (1984-1994)**". The present document supplements this report and is intended to keep cartographic planning abreast of changing scientific, technological and programmatic requirements.

Most of the topics in this supplement relate to new or rapidly developing opportunities and needs, especially in regard to digital cartography. The use of digital techniques in cartography enhances the ability to overlay multiple data sets and allows rapid, economic revisions of maps. The relevance of cartography and geodesy to planetary science is reviewed in section 3; section 4 provides a general discussion of digital cartography and its use in planetary science; section 5 describes typical computer-based cartographic work stations that will be needed by planetary scientists and section 6 presents cartographic plans for planetary objects not considered in the original ten-year plan.

The appearance of a supplement shortly after publication of the ten-year plan reflects the current vigor of the field. Although the ten-year plan provides the framework for cartography independent of techniques, the Planetary Cartography Working Group considers that it must be supplemented because of new needs, new opportunities, and advances in supporting technology. Continuing consideration of cartographic issues is needed to maintain flexibility; the opposite attitude would condemn planetary cartographers to a rigidity incompatible with the dynamic service expected by planetary scientists and mission planners.

3. RELEVANCE OF CARTOGRAPHY AND GEODESY TO PLANETARY SCIENCE

3.1 Introduction

Maps have been used since antiquity. The earliest explorers used available maps or made new ones to document their voyages and to help future exploration. Current exploration is focused on the Earth's seafloor and the Solar System. Maps of the planets, like those of the Earth, are used to depict surface features, to plan further exploration, and to show relationships among different types of data. By providing a coherent view of planetary surfaces, maps are crucial for understanding the geological evolution of planetary bodies.

Cartography encompasses geodesy, planimetric mapping, and topographic mapping, all of which contribute to the accurate depiction of a planet's surface. The accuracy of maps, i.e., how precisely the position of features are shown, depends on how well various *geodetic* parameters have been established. These parameters include defining the position of the pole and the shape of the body, and establishing a reference zero-meridian so that surface features can be located within a planet-wide coordinate system. For spheroidal bodies, these parameters can be established by well-developed methods, but the techniques are poorly defined for irregularly shaped bodies such as asteroids. Once a coordinate system is established then *planimetric mapping* can be conducted to show the locations of specific features on the surface. *Topographic mapping* shows the vertical dimension of the surface. The combination of radar or laser altimetry with photogrammetry derived from stereoscopic images is a powerful tool for obtaining topographic data. Using this technique, accurate topographic data have been obtained for about 20 percent of the Moon. In the future, radar altimeters will be used to obtain topographic data for Venus via the Magellan spacecraft and for Mars via the Mars Observer spacecraft.

3.2 Relevance of maps for scientific investigations

Planetary maps are used extensively in scientific investigations. Planimetric maps, mosaics, and shaded-relief drawings depicting surface features are the first products prepared from each mission. They are used as bases on which nearly all subsequent scientific information is displayed.

Some planetary maps consist of digital data arrays that display spatial relations in two or three dimensions. Cartographic data can be manipulated much more easily when they are assembled as digital arrays. Standard computer operations provide the flexibility to rearrange the data to determine the optimum map projection, scale, and format. This flexibility greatly enhances the interpretation of large arrays of data. For example, the Mars Observer instrument payload will generate a wide range of data sets amenable to this style of analysis (Table 3.1).

Planetary exploration has stimulated the development of highly sophisticated direct- and remote-sensing instruments. Data from many of these instruments are used most effectively as map displays in which spatial relations can be seen and correlated with other data. For example, concentrations of many elements can be measured from orbit by gamma-ray spectrometers and on airless bodies by X-ray fluorescence spectrometers; infrared spectrometers provide information on elemental and mineralogic composition; gravity anomalies can be determined by accurate spacecraft tracking. Cross-correlation of these multiple data arrays, as demonstrated for the Moon by a consortium of investigators representing a variety of instruments, can be carried out for Mars and other planetary bodies. Having the data in digital arrays greatly expedites cross-correlations and leads to better interpretations of planetary history.

3.3 Relevance of maps to future planetary exploration

An important use of maps in planetary science is in planning future exploration. Each successive mission builds on data derived from previous missions. For example, maps of the Moon made from Earth-based telescopic observations were used to plan exploration by the Ranger, Surveyor, and Lunar Orbiter missions; results from these unmanned missions were then used to plan for early Apollo landings. Early Apollo orbital flights and lander missions acquired data that were used to select the Apollo sites where later landers collected samples of the Moon.

Long-range planning for the exploration of Mars is following a similar sequence. The first maps of Mars were drawings of features seen from Earth. Images of a small part of Mars, supplied by the Mariner 4, 6, and 7 flyby missions, provided planning materials for the orbital Mariner 9 mission. Data from this mission, in turn, enabled the compilation of planetwide maps that displayed scientific results of the mission and served as planning charts for the Viking mission. The Mars Observer mission will acquire planetwide geochemical and geophysical data, and high-resolution photographs. These data, combined with existing maps generated from the Viking mission, will enable the scientific rationale to be developed for future missions to Mars including sample return and eventual exploration by humans.

3.4 Summary

Much of the growing understanding of planetary surfaces and interiors, and the processes that have shaped them, results from the increasing sophistication and accuracy with which planetary surfaces can be displayed. Maps and related topographic and geodetic products are essential for the exploration of all solid objects in space.

Maps, atlases, and globes, as well as three-dimensional views and motion-picture sequences, are also powerful educational media. These displays, supplemented by graphs and charts, present complex scientific data and ideas to students and the public in a more easily comprehensible and compact form.

Table 3.1 Mars Observer Standard Geoscience Data Products

Visible and Infrared Mapping Spectrometer (VIMS) • Global maps with ~1 km to ~40 km pixels depicting radiances for particular wavelengths or combinations of wavelengths. • Derived global maps with ~1 km pixels depicting presence and/or abundance of particular minerals (e.g., nitrates or carbonates). • Detailed maps covering smaller areas with lithologic units portrayed. Based on snapshot modes of 40x40 km spatial dimensions and full spectral samples.
Thermal Emission Spectrometer (TES) • Global maps with ~10 km pixels depicting emissivity for particular wavelengths or wavelength combinations (i.e., color composites). • Global maps depicting rock silica content and other parameters related to mineral chemistry. • Global maps depicting variety of thermophysical parameters such as thermal inertia.
Gamma Ray Spectrometer (GRS) • Global maps with ~350 km pixels depicting abundances for various elements. • Global maps of atmospheric pressure in latitude bands.
Radar Altimeter (RA) • Global maps with ~10 km pixels showing elevation, slope, reflectivity, roughness, emissivity.
Mars Orbiter Camera (MOC) • High resolution (1.4 meter pixels) images covering 2.7x2.7 km. • Images with resolutions of 300 meter pixels at best to monitor variable features.
Magnetometer • Global map with ~10 km pixels depicting remnant magnetic field.
Radio Science • Global map depicting geopotential heights and anomalies.

Note: VIMS, TES, MOC, and RA reflectivity and emissivity maps covering different times during the 2 Earth years (1 Mars year) of the mission would probably be produced to show seasonal and secular changes.

4. DIGITAL CARTOGRAPHY

4.1 Introduction

Traditionally, maps and photomosaics have been printed on paper as the final product. With digital techniques, it is now possible to prepare more diverse maps and the number of useful combinations of *base maps* (planimetric, topographic, etc.), *interpretive maps* (geologic, geophysical, etc.), and maps of remote sensing data (gravimetric, elemental distributions, etc.) has increased substantially. Many of these combinations are simply working sets and can be assessed on video screens, thus avoiding the need for photographically-prepared preliminary versions. Those deserving wide distribution can be printed on paper and reproduced in large numbers.

Traditional maps and photographs are generated with the dynamic range of the human eye in mind. However, most remote sensing data involve wavelengths, dynamic ranges, and intensity levels that cannot be seen directly. For example, a television image typically discriminates 256 shades of gray, whereas the eye can distinguish only about 16. Digital processing of remote sensing data can do much to enhance its utility and presentation, and to reduce the cost and time to produce cartographic materials. Match lines in mosaics can be eliminated; albedo and reflectance data can be normalized over large areas; contour maps and shaded relief maps can be prepared automatically; boundaries between terrain classifications derived from combinations of remote sensing data can be generated in the computer. Most important, the investigator can interact directly with the data on cathode ray tube display work stations. Digital cartography involves three principal data sets: digital data bases, digital image models, and digital terrain models.

Digital data base

In order to combine several types of data into a single map, it is necessary for the data to be in a compatible format. To achieve this, all data are resampled as pixels which are defined as fractions of a degree of latitude and longitude of the equator. Thus, at higher latitudes the area covered by the pixel is the same as at the equator, but its longitudinal dimension is increased by the inverse of the cosine of the latitude. The advantage of this system is that the entire body is covered by a single array of pixels. Once the data are formatted in this fashion, maps of any area can be compiled into any map projection. The theoretical relationship between *map scale series* and *pixel dimensions* is shown in Table 4.1. Although this is not a rigorous mathematical relationship, it is based on the empirical proposition that image map resolution should be five to ten pixels per millimeter. The meter equivalents of fractional degree pixels for each planet are shown in Table 4.2.

Digital image models

When the digital data base is displayed planimetrically, it is called a *digital image model (DIM)*. Each pixel may contain a numerical value (e.g., "grey level") derived from each instrument, or interpretation (e.g., geologic unit). Subsequent maps may then combine these values in a manner that is scientifically useful.

Digital terrain models

Elevations may be stored for each pixel and configured as a map termed a *digital terrain model.* Elevation data can be derived from stereoscopic images, altimeter measurements from spacecraft, or from Earth-based radar measurements. At present, only a few digital terrain models can be compiled because of the sparsity of suitable data, but future missions will enable the technique to be more widely applied.

4.2 Digital cartographic products from existing data

Some of the maps described here are included in the 10-year plan, but can now be compiled in digital formats. For example, the generation of Mars digital maps is a new activity underway to support the Mars Observer mission.

Table 4.1. Recommended digital mapping format and the corresponding map scales. Recommended mapping with data to be gathered on future programs is indicated by parentheses.

	MAP SCALE				
PIXEL SIZE (degrees lat-long)	INDEX MAPS	1:10M-1:25M	1:5M	1:2M	≤1:500k
1/16	all	Iapetus Umbriel Titania	Tethys Dione Rhea Ariel	Mimas Enceladus Miranda	
1/32			Europa Io		
1/64			Mercury Ganymede Callisto (Triton)		
1/128				(Io) (Europa) (Triton*)	(Ganymede) (Callisto)
1/256				Mars	(Io*) (Europa*)
1/512				(Venus)	(Ganymede*) (Callisto*)
1/1024					Mars*
1/2048					(Venus*) Mars*

** Recommended high-resolution mapping of selected areas.*
M = million, K = thousand.

Table 4.2. Meter equivalents of digital model pixel sizes. Mean radii are given for highly irregular satellites (Phobos, Deimos, Amalthea, and Hyperion).

PLANET (radius, km)	PIXEL SIZE IN M						
	DIGITAL SCALE (deg/pxl)						
	1/16	1/32	1/64	1/128	1/256	1/512	1/1024
Mercury (2439)	2660		665				
Venus (6052)	6602					206	
Mars (3385)	3692				231		058
Phobos (11)	012						
Deimos (6)	007						
Amalthea (215)	234						
Io (1816)	1981	990		248	124		
Europa (1563)	1705	852		213	107		
Ganymede (2638)	2878		719			090	
Callisto (2410)	2629		657			082	
Mimas (197)	215						
Enceladus (251)	274						
Tethys (524)	571						
Dione (559)	610						
Rhea (764)	833						
Iapetus (724)	790						
Hyperion (148)	161						
Miranda (242)	264						
Ariel (580)	633						
Umbriel (595)	649						
Titania (805)	878						
Oberon (775)	845						
Triton (2200)	2400		600	300			

Mars medium-resolution digital image model

A set of approximately 4700 Viking Orbiter images covers all of Mars at resolutions of 150 to 300 meters per pixel, and with solar zenith angles averaging 70 degrees. This set was used to compile the existing 1:2,000,000 controlled photomosaic series, and will be compiled as a digital image model to support science investigations and the Mars Observer mission. The scaling of the digital image model mosaic is 1/256 degree per pixel (approximately 231 meters per pixel). Selected segments of the mosaic will be published conventionally as revised 1:2,000,000 controlled photomosaics with contour overprints in areas where topographic data can be compiled.

Mars medium-resolution digital terrain model

This database is being compiled from the 1:2,000,000 topographic maps. The model will be encoded at 1/64 degree per pixel with an elevation accuracy of ±500 meters. It can be enlarged four times by the user to match the image model, but is not encoded at that sample size because the input data do not have sufficient resolution. The database will be distributed in both digital format (probably on CD-ROM disks) and as a printed topographic map.

Mars high-resolution digital image model

Areas of scientific interest are being compiled with available high-resolution coverage (10 to 150 meters per pixel). Compilation of this model will replace the manual compilation of controlled photomosaics in the 1:500,000 series. Digital recompilation of existing 1:500,000 maps will be done in support of specific studies. New compilations will be published at 1:500,000-scale and distributed in digital format.

Mars high-resolution digital terrain models

Areas of special interest are being compiled for publication as topographic maps at 1:500,000 scale. These compilations are being converted for distribution in digital format. The expected number of these models is small, because only part of the Viking data are adequate for high-resolution topographic measurements.

Galilean and saturnian satellites digital image models

1:5,000,000-scale mapping based on Voyager images is complete for Io, Europa, and Ganymede using conventional compilation of mosaics and airbrush compilation of final maps. A digital image model of Callisto will be compiled in both digital form and as 1:5,000,000-scale controlled photomosaic quadrangles; resolution is 1/64 degree per pixel, or about 700 meters per pixel. Compilation of an image model of Rhea, at 1/16 degrees per pixel (417 meters per pixel), is complete.

Digital image models of airbrush maps of the planets

Existing airbrush maps are being digitized to facilitate their use as base materials for geologic mapping and to support future map series. Digitized airbrushed index maps of 14 solid-surface bodies (all major objects except the satellites of Uranus and Neptune) have been made at 1/16 degrees per pixel and used extensively both as indexes and for mission planning.

4.3 Digital cartographic products from future missions

Future missions will return a wide variety of data that should be compiled in a digital cartographic format. The digital image models discussed below will be used as bases for published mosaics and airbrush maps. The scales planned for map publication remain as shown in the original ten-year plan.

Venus. Radar backscatter images from the Magellan mission will be obtained for at least 70 percent of the planet at 225 meters per pixel. These images will be used to produce a 1:50,000,000-scale planetwide map and 1:5,000,000-scale semicontrolled photomosaics. At least 15 percent of the Magellan radar data will be mosaicked in high-resolution mode (75 meters per pixel) to serve as bases for high-resolution maps. Controlled digital image models will be compiled following the Magellan mission. Digital image models of radar emissivity, roughness, and reflectivity will also be made, as will digital terrain models (from radar altimeter data) with a nominal horizontal sampling interval of 10 km. These products will also be compiled in both interim and final form.

Mars. Digital products to be compiled from Mars Observer data will include maps of mineral species and their abundances derived from the visible and infrared mapping spectrometer; Thermal Emission Spectrometer data; global radar elevations; radar backscatter and radiometry data; elemental abundances from the Gamma Ray Spectrometer; and imaging data.

Jovian satellites. Digital image models will be made from Voyager images and from both Solid State Imaging (SSI) and Near Infrared Mapping Spectrometer (NIMS) data from the Galileo mission.

Saturnian satellites. Digital image models will be made from Voyager 2 data of Dione, Iapetus, Enceladus, Tethys, and Mimas.

Uranian satellites. Digital image models will be made from Voyager 2 data of Miranda, Ariel, Umbriel, Titania, and Oberon.

Neptunian satellites. Digital image models will be made from Voyager 2 data for Triton (if the surface is not obscured by clouds) and possibly of Nereid.

4.4 Recommendations

The rapid advances in digital cartography do not alter the requirements for the map series defined in the published ten-year plan. Digital, rather than manual, cartographic methods will be used to compile parts of those series, greatly increasing the versatility of the data. The inexpensive conventional paper maps will continue to be available to a very large number of investigators and educators. In addition, cartographically-structured digital files will be available to those who can make effective use of them. In order to exploit the advantages afforded by digital cartographic techniques, the following recommendations are made:

- **Mars**: Digital image models should be compiled with the highest resolution Viking Orbiter images available covering the following areas of Mars: Chasma Boreale, Chasma Australe, Candor Chasma, Mangala Valles, Olympus Rupes, Memnonia Regio, Elysium Montes, Kasei Valles, Nylosyrtis Regio, and Appolinaris Patera. These are areas currently being studied as potential landing sites for future missions. Additional sites should be included as necessary to support other scientific investigations. Digital topographic models should be compiled for areas where high-resolution topographic data are available in conjunction with digital image models.

- **Other planets**: A digital image model of Mercury should be compiled with Mariner 10 data (Table 1); a digital terrain model based on Earth-based radar altimetry should be compiled in register with the digital image model. Radar maps and digital models of Venus from Magellan data should be prepared, as discussed in section 4.3.

- **Satellites of the outer planets**: Digital image models should be compiled for each of the satellites of the outer planets using Voyagers 1 and 2 data (Table 1).

- **Moon**: Compilation of a medium-resolution digital image model of the Moon is highly desirable. However, synoptic lunar data are not available in digital form, nor is the existing geodetic net adequate to control such a database. The working group therefore recommends that alternative digital methods (e.g., digitizing existing analog data and construction of new geodetic control nets) be evaluated for feasibility and application to future programs until new lunar data can be obtained.

5. DIGITAL CARTOGRAPHY REQUIREMENTS

5.1 Introduction

The availability of digital cartographic data will open new opportunities for the planetary community. In addition to the distribution of paper copies to meet the needs of the larger scientific community, distribution of digital data will allow extraction of quantitative information and manipulation of the data in ways not otherwise possible. The requirements for using these data are discussed in this section and examples of processing systems are presented.

5.2 Requirements for analyses of digital cartographic data

Maximum use of digital cartographic data will occur if the data are widely distributed and if investigators have the means to use the data. The NASA Planetary Data System is expected to play an important role in providing access to these data. The means to analyze digital cartographic data are similar to those for image processing (Fig. 5.1). The operations include input, processing, and output. Because cartographic data are extensive, input can be time consuming, involving finding and loading the data files into temporary storage on a computer system. Thus, high volume media must be accessed rapidly. Cartographic data and ancillary information should be included in standard formats and units to compute the location of a pixel on the surface, and to show the quantitative relationship between the brightness of a pixel and the values of the physical units portrayed by the data. The processing procedures to generate the cartographic products should also be included with the data. In some cases, the data should be distributed in integer or floating point format to retain the information inherent in the large dynamic range of many data sets.

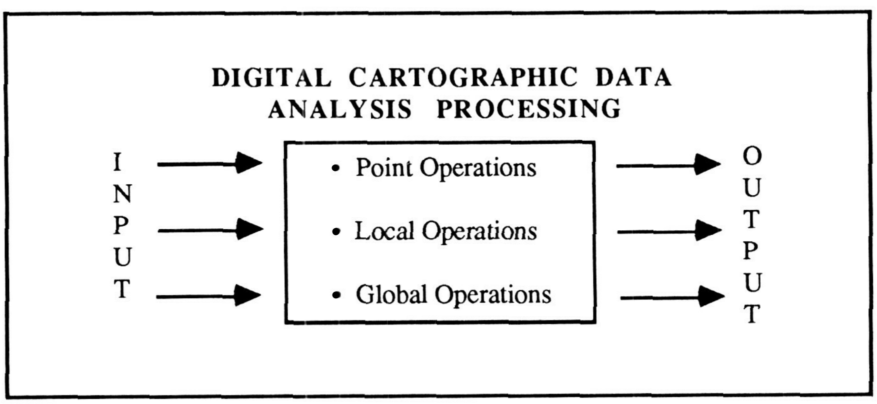

Figure 5.1. *Flow chart depicting typical digital cartographic analysis session. Input could be from a variety of media (e.g., tape, CD-ROMs), a large number of processing operations could be performed, and output could be an image, numbers, contour maps, etc., onto printers, plotters, or film.*

Processing of cartographic data will follow the same broad categories defined in image processing. Users should be able to display, enhance, and filter the cartographic data; to generate color composites; and to extract numerical values for pixels or groups of pixels. In addition, it should be possible to overlay and cross-correlate two or more data sets. These requirements can be met with modest image processing systems.

Cartographic data will be provided in a simplified and standardized geometric format, such as a sinusoidal equal-area projection. Users can then geometrically reformat the arrays for optimum viewing. Many investigators will use this capability only on small (CRT-sized) segments of digital maps. Requirements for hard copy may be satisfied by photographing video images. Other users will require the capability to transform large images to standard map projections, to make high-resolution film images (both black and white and color), and possibly to make graphs of contoured data using automatic plotters.

5.3 Systems for analysis of digital cartographic data

Planetary scientists will have a range of computing needs, from simple systems to display parts of the data and conduct basic processing, to more advanced systems to perform autocorrelation and cross-correlation operations, geometric operations, and to generate high fidelity photographic products. Thus, no single work station will satisfy the entire community, but must be matched to specific requirements.

A minimum configuration for digital cartography is shown in Figure 5.2. Based on a microcomputer with a modest image frame buffer and display, several such systems are commercially available. Input is assumed to be from an optical disk, such as a CD-ROM, which offers high data volume (550 megabytes), relatively rapid, random access, and low cost. A terminal, disk storage, and printer complete the system. Figure 5.3 shows a more powerful system, based on a larger computer (such as a VAX 8200), augmented with an array processor. This system could be used to generate digital cartographic data in addition to conducting analyses. Large volumes of data can be transferred to system disk memory as the need arises for more efficient input/output. This system could be equipped with a film recorder and laser printer to produce high quality output. The system is shown networked to other facilities for electronic transfer of data.

5.4 Recommendations

The following recommendations are made regarding digital cartographic requirements and systems for analysis of digital cartographic data:

- Data processing work stations must be provided to planetary scientists to utilize digital cartographic data.
- CD-ROMs should be developed as high volume, random access, low-cost means for distributing digital cartographic data.

- The J-2000 reference system should be adopted as the standard for digital cartographic data.
- Ancillary information must be included with the cartographic data in order to understand the processing history, data geometry, and relations between map brightness or color values and other data.
- Data and ancillary information should be distributed in standard format data units.

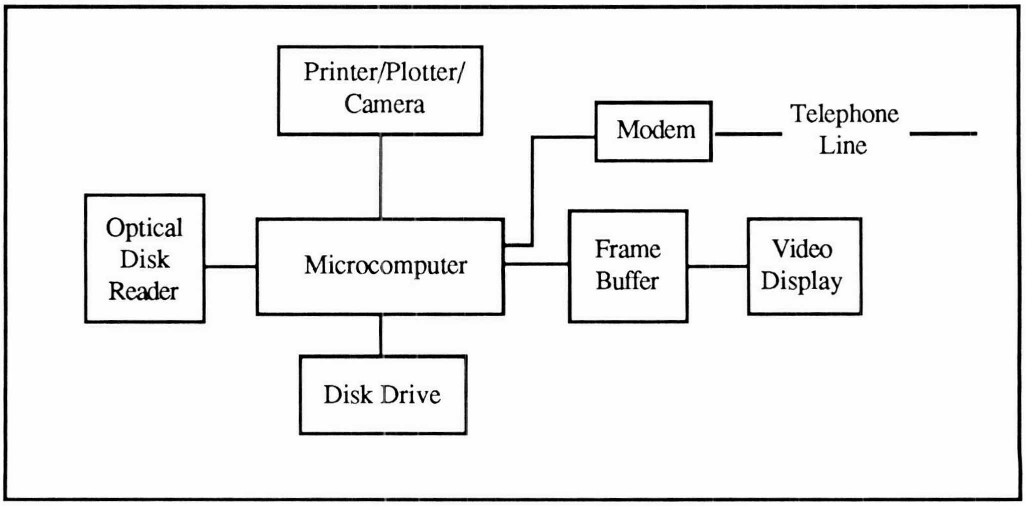

Figure 5.2. Minimum system for digital cartographic data analysis. A keyboard and terminal would also be included.

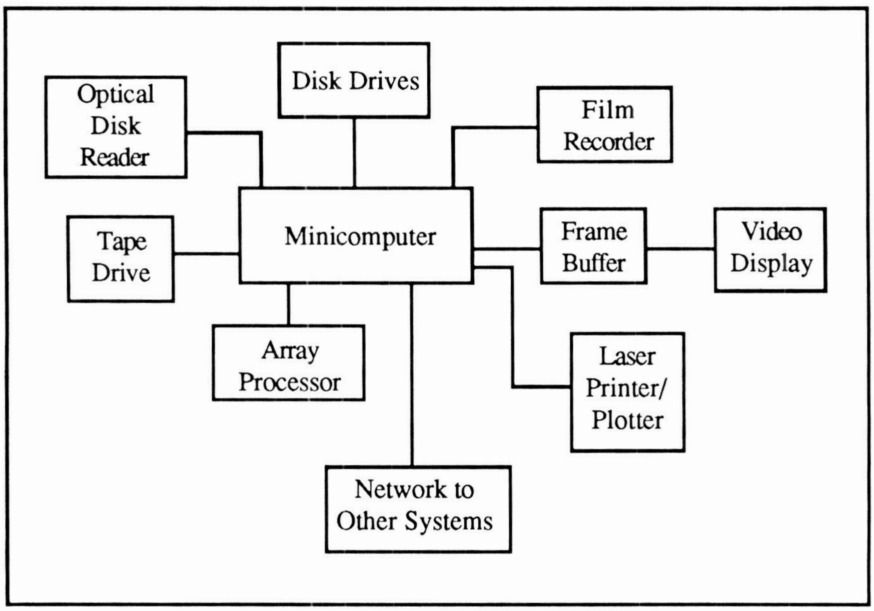

Figure 5.3. Advanced system for digital cartographic data analysis. Data base management might be done either by software or hardware implementations. Several interactive terminals would also be included.

6. CARTOGRAPHY FOR PLANETARY OBJECTS NOT INCLUDED IN EXISTING PLAN

6.1 Introduction

Several planetary objects were not addressed in the ten-year plan, either because projects requiring cartographic support did not exist, or because map specifications had not been defined. These objects include the Moon, Mercury, and irregularly-shaped satellites such as Phobos.

6.2 Moon

Earth-based telescopic pictures and Lunar Orbiter 4 and 5 photographs of the far side have been used for preparing primary base maps of the Moon, although the positional accuracy obtained from these sources is poor. Apollo 15, 16, and 17 carried mapping and high-resolution cameras and were important missions for mapping parts of the Moon at high resolutions (~10 m) and for obtaining good topographic control (±500 m). The coverage, however, was limited to equatorial regions. The Soviet Zond 6 and 8 pictures are useful additions but are also limited in coverage and control. Hence, it is not possible to produce global maps of uniform quality because of the variety of data sets.

Control networks are also limited because of variable resolution and quality. Moreover, there are insufficient data to merge the different control networks. For example, the Apollo network is adjusted to Apollo 15 (revolution 44) tracking ephemeris and the Koziel libration model with an origin at the *center of mass*. The best Earth-based telescopic network, on the other hand, gives coordinates of points with origin at the *center of figure*. Because it is not possible to make accurate measurements or correct for distortions on Lunar Orbiter pictures, positional data are poor. However, a unified network using best available data is currently in preparation.

The most popular global maps of the Moon are the 1:5,000,000 scale sheets of the near side, the far side, and the polar regions. The original series was published in the 1960s and is now out of print. New maps of the far side and the polar areas have been produced, and a new map of the near side should be published to complete the series. This set of maps is important for global lunar research projects and for planning new missions to the Moon.

6.3 Mercury

Mariner 10 imaged about 40 percent of the surface of Mercury with spatial resolutions of 0.1 to 1 kilometer per pixel. However, unfavorable illumination, relatively poor image resolution, and the restricted areal coverage make Mercury one of the least explored terrestrial planets.

Acquisition of Earth-based radar data of Mercury began more than a decade ago. Goldstone data have been acquired using both S-band (12.5 cm) and X-band (3.5 cm) dual polarization radar systems. Goldstone data are produced in the form of backscatter images for regions within 25 degrees of the equator and radar profiles for regions within 11 degrees of the equator. Arecibo elevation data were acquired at 12.6 cm wavelength from 1978 to 1984 for regions between 12 degrees north and 5 degrees south. Each Arecibo track covers between 20 to 90 degrees in longitude, with a resolution of 0.15 degrees in longitude and 2.5 degrees in latitude.

The radar data for Mercury cover regions imaged during the Mariner 10 mission and equatorial regions for longitudes not yet observed by spacecraft imaging systems. Thus, radar offers important and unique data for understanding the mercurian surface and interior. The data exist in two forms: topographic profiles and backscatter images, both of which can be used for mapping. Topographic data could be displayed on the existing 1:5,000,000 shaded relief maps by over-printing the elevation ground track as a relatively thick line. Topography should be portrayed as a thinner line immediately above the ground track, i.e., the ground track should also be used as the abscissa for a plot of elevation versus downtrack distance. The map margin should contain information documenting the acquisition and processing of each track.

The existing 1:15,000,000 global shaded relief map should be overlain with the backscatter images which have approximately 10 km pixels, placed at the appropriate locations. The 10 km pixel widths are just accommodated at the 1:15,000,000 scale.

6.4 Irregular objects

Many satellites, asteroids, and comets have very irregular shapes and rotations which pose special problems for the production of maps. In the past, imaging of these objects has been largely incidental to primary mission objectives and cartographic products have not been well organized. Future missions, however, may encounter asteroids and comets and produce sufficient images for detailed maps. When comet rendezvous and asteroid flyby missions occur, production of maps and topographic data and maps of time-dependent topography will be needed. Thus, an improvement in handling mapping data from irregular objects is required.

Interpreting the physical properties and geologic history of an irregularly shaped satellite or asteroid requires much the same information as for planets, such as the following:

Size and shape. Accurate volume determination is needed to calculate mean density, a fundamental goal for any program of exploration of asteroids, comets, or satellites. The volume should be determined to better than 5 percent to allow useful comparisons with densities of candidate materials. A 5 percent volume error is just less than 2 percent radius error. Fundamentally, a network of control points must be determined that is dense enough to constrain the volume and to model the major topographic features (crater shapes, major slopes, cracks, grooves, etc.). The greater the irregularity of the body, the more control points will be needed.

Maps. The context of surface features can only be well appreciated by usable maps. For objects of very irregular shape this poses substantial problems in map projection, discussed below. There is no substitute for good maps; the laborious mapping by hand of Phobos and Deimos delayed discovering the critical patterns of grooves on Phobos and the patterns of downslope movement of debris on Deimos, and leaves considerable uncertainty in the orientation of these key features.

Photometry, radiometry. Accurate disk-resolved photometry requires knowing the orientation of the surfaces being illuminated and sampled. A quantitative model of the shape of the surface is necessary and is usually not well approximated by ellipsoidal models. Even studies of the relative photometric behavior of nearby areas is hampered on Phobos and Deimos by poor knowledge of the rapidly varying slopes.

Surface processes. Knowledge of local slopes is needed to interpret surface processes, be it crater modification, landslides, modification of grooves, or the development of active centers on comet nucleii. A quantitative knowledge and usable presentation of topography at small scales is needed.

Structural studies. Coordinates of surface points are required to determine the size and the orientations of structures exposed on the surface. The obvious examples are the Phobos grooves which are arranged in sets of roughly parallel striations. As specified above for global shape, a sufficiently dense network of control points is vital to determine local topography and surface orientation.

Sketch maps of Phobos and Deimos have been made by Duxbury and Thomas. Sketch maps have also been produced by Thomas for Amalthea, Janus, and Epimetheus. Although the Phobos and Deimos maps have been very useful scientifically, their manual preparation and simple projections leave much to be desired.

Processing of some images of Phobos and Deimos has been done with the assumption of ellipsoidal shapes. For some views this assumption has been adequate; however, the application of one shape to all views is inadequate for many investigations. Control points have been developed for Phobos and Deimos by Duxbury and Callahan by stereoscopic measurements of Viking Orbiter images, but have not been used to produce topographic maps. Volumes have been estimated by fitting triaxial ellipsoids to the coordinates, but the volumes may be uncertain by 10 percent or more. Sizes of other satellites have been given as dimensions measured in primary directions but volume uncertainties are substantial (20-30 percent).

Future approach

Good quantitative mapping of irregular objects can be done with present technology. Beginning with stereo determination of control points, application of limb and terminator data (and in some instances, photometric approximations) can yield good sets of surface coordinates. Derivation of surface coordinates then allows generation of: (1) topographic maps, (2) surface feature maps, and (3) knowledge of surface orientation coordinates for use in study in photometry and radiometry. Some objects can be represented by several fairly smooth intersecting surfaces (Deimos); others are more random (Hyperion, Amalthea). Maps of the surfaces may have to be subdivided for certain areas, in addition to the global maps in which the large regional slopes cause great distortions. The extent to which a single mapping scheme may be generalized to many different planetary objects needs to be investigated.

Available technology and software used in computer-assisted design or a variety of other fields that deal with complex three-dimensional description can be applied to the problems of multiple projection of irregular objects and the retrieval of surface orientations in individual images. Major obstacles to this scheme include the limited quality and quantity of spacecraft target coordinates.

Specific goals

The major goals for the cartography of irregular objects should include the generation of:

1. A control point catalog sufficiently dense to constrain the volume to <5 percent uncertainty.
2. A global analytic topography model of the surface to specify surface orientations and positions of areas within specific image frames or footprints of other remotely sensed data.
3. One or more shaded relief maps per object to present topography and surface features in usable projections. Digital maps will probably be a major tool so they can be projected for specific investigations.

6.5 Recommendations

- Compile and publish the nearside 1:5,000,000 scale map of the Moon, using the new Davies unified lunar control network.

- Procure data from the Lunar Geophysical Orbiter (LGO) mission to support the generation of a uniform improved control network for the entire lunar body. This network needs to be of sufficient quality to support 1:1,000,000 scale mapping.

- Earth-based radar data for Mercury should be utilized by over-printing topography on existing 1:5,000,000-scale maps and by over-printing radar backscatter data on the existing 1:15,000,000-scale maps.

- Digital radius and image models should be made of Phobos, Deimos, Amalthea, and Hyperion. These models should be made at resolutions of approximately 1/16 degree per pixel, resulting in arrays of 2048 lines by 4096 samples. Few of these small, irregular bodies have sufficient imaging coverage and resolution to produce complete sets of these recommended products. However, the Phobos data sets from Mariner 9 and Viking Orbiters give complete stereo surface coverage at 50-200 m resolution. Therefore, the Phobos data set should be used to study the unique mapping problems of small bodies in detail prior to the Comet Rendezvous Asteroid Flyby mission which will require this capability.

- The specific cartographic products for Phobos should include: a global topographic model of the entire surface; modified conformal projections of controlled photomosaics in the form of shaded relief maps; and high resolution topography contours in limited areas. The global topographic model should be analytic (e.g., harmonic expansion) if reasonably accurate; otherwise, a discrete table look-up by latitude-longitude bins would have to be used. Sufficient Phobos imaging data exist to produce global shaded relief maps at a scale of 1:50,000. Limited areas have sufficient resolution to support 1:10,000 scale products. Additionally, these data can provide elevation data for contouring at 200 m increments. It is recommended that priority for the limited 1:10,000 shaded relief and topography maps be in support of site selection for the Russian Phobos mission.

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16. Abstract

Planetary maps being produced today will represent views of the solar system for many decades into the future. The primary objective of the planetary cartography program is to produce the most complete and accurate maps from the hundreds of thousands of planetary images in support of scientific studies and future missions. This document emphasizes the utilization of digital techniques and digital bases in response to recent advances in computer technology.

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