PLANETARY MAPPING WITH PHOTOGRAMMETRY

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ABSTRACT

Images of planetary bodies usable for making topographic maps have been, and will continue to be, acquired by many planetary missions. For photogrammetric compilation, special techniques and instrumentation have been developed to accommodate such unconventional factors as images from line-scan cameras, very narrow fields-of-view, weak model geometries, high oblique angles, and atmospheric haze. We have used photographs from Apollo missions to compile topographic maps of the Moon at various scales. For Mars, applying analytical photogrammetric methods to 1,160 high-altitude (up to 37,000 km) Viking Orbiter pictures, a planetwide control network has been established that has produced about 5,000 control points; these control points are being used to map Mars systematically at a scale of 1:2,000,000. For future mapping of Venus' topography, a synthetic-aperture radar compilation system has been developed on the AS-11AM analytical stereoplotter. A contour map of the southern hemisphere of Miranda, the smallest and innermost satellite of Uranus, has been compiled from Voyager 2 stereoimages. This paper also discusses future directions for planetary mapping .

I. INTRODUCTION

In contrast to topographic mapping of Earth, mapping of other planets and satellites presents many unprecedented problems: (1) other bodies have no oceans and therefore no sea level to provide a reference surface for elevations; (2) their surfaces and atmospheres have photometric properties different from Earth's; (3) data for deriving topography come from a variety of sources, commonly of different formats, resolutions, and precision; and (4) control networks, once established, are not as precise as those on Earth, due to low image resolution, image distortion, and errors in tracking data. An example of the second problem is that Venus' atmosphere is so dense that its surface cannot be seen from orbit with conventional imaging systems. Consequently, Venus must be imaged with a radar system, which requires development of new techniques for mapping.

Data to support topographic mapping are available for only five of the nineteen planetary bodies explored thus far: the Moon, Mars, Venus, and, in limited experiments, the Uranian satellite Miranda and the Martian satellite Phobos.

II. PLANETARY TOPOGRAPHIC DATA

Remote-sensing data obtained from devices with a wide range of wavelengths play an important role in planetary topographic mapping. Both imaging and nonimaging data are used.

Film cameras: Film images have been returned by several lunar missions. Many of these images were taken by cameras designed specifically for photogrammetric use; that is, the cameras incorporated reseau patterns and fiducial marks, and their optical characteristics (such as focal length and distortion patterns) were calibrated prior to their use.

Many pictures were taken from the orbiting Apollo command modules by hand-held cameras, which were intended primarily for mission documentation. The images were usable, however, for mapping selected areas on local reference datums (Wu, 1969). Photogrammetrically calibrated hand-held cameras were used by the astronauts on the lunar surface for scientific documentation of the geologic traverses; the cameras also enabled compilation of many large-scale maps documenting the location of samples.

The Hycon topographic camera was the first system carried beyond Earth's orbit that was specifically intended for photogrammetric use. It had a 350-mm focal length and a 125 X 125 mm image format. The camera obtained 193 frames for Apollo 14, and it was intended for high-resolution mapping of future Apollo landing sites.

Not until the Apollo 15, 16, and 17 missions was extensive lunar photogrammetric mapping attempted (Dietrich and Clanton, 1972a, b; McEwen and Clanton, 1973). These missions carried a mapping system that included film cameras specifically designed for photogrammetric mapping. The system included a mapping camera which was aligned with a star camera, a very high resolution optical-bar panoramic camera, and a laser altimeter. The system was used to map about 20 percent of the equatorial region of the Moon (Wu, 1985).

<u>Television (vidicon) cameras</u>: Television cameras have been used for planetary exploration since the Mariner 4 Mission to Mars in 1965. They are useful because they do not require return of the film from the very distant planetary bodies. High-resolution imaging is possible through the use of telephoto lenses.

Formats of television images are small, typically 800 lines by 800 samples of image data on an 11 X 11 mm vidicon image plane. Electronic readout of vidicon images introduces severe geometric distortions that must be corrected before the images can be used for mapping.

Early returned planetary images were the sequences of television images taken of the Moon by Rangers 7, 8, and 9. The Army Map Service (now the Defense Mapping Agency, Topographic Center, or DMATC) made several large-scale maps from these images, even though the baseline between them was more nearly vertical than horizontal (Arthur, 1962).

Geometric accuracy of images will be greatly improved with the substitution of charge-coupled devices (CCD's) for vidicon tubes, which will be done on the Galileo Mission to Jupiter in the mid-1990's (Klaasen et al., 1982). However, photogrammetric problems resulting from small formats and narrow-angle lenses will remain.

<u>Scanning cameras</u>: Scanning cameras form images in continuous strips along the spacecraft's suborbital track. Scan lines are perpendicular to the orbital track and are formed by a moveable mirror synchronized with the orbital velocity of the spacecraft. These systems have been

used extensively on Landsat-type spacecraft in Earth's orbit. Facsimile cameras are variants of this design and have been used on lander spacecraft. The Soviets began to employ facsimile cameras on lunar landers and roving vehicles in 1966 and on Venus landers in 1975. The U.S. used similar devices on the Viking Mars landers in 1976: the imagery of these cameras enabled the making of topographic maps of each lander site at a scale of 1:10 and a contour interval of 1 cm.

Synthetic Aperture Radar: Testing with synthetic aperture radar (SAR) imagery for use in topographic mapping is currently in progress in offices of the U.S. Geological Survey (USGS) in Flagstaff, Arizona (Wu et al.,1988). Contour maps have been made by using imagery from the following systems: SeaSat (the New Orleans and Los Angeles areas), SIR-B (Mt. Shasta) NASA 102A (Mt. St. Helens), and ERIM X-C-L (the Spitsbergen area, Norway).

III. TECHNIQUES, EQUIPMENT, AND MAPPING PROGRAM

Equipment used for photogrammetric compilation in the planetary mapping program includes various types of analytical stereoplotters (AP/C, AS-11A, AS-11AM, AS-11B1) and other standard photogrammetric equipment. New techniques and new software have often been developed to accommodate specific data for a particular planetary body. In addition, the planetary mapping program is supported by the USGS Image Processing Facility in Flagstaff, Arizona, which works with various computers, array processors, film-scanning and -writing devices and software for pre- or post-processing of data for contrast enhancement, rationing images, spatial filtration, and many geometric corrections and transformations. So far, the planetary topographic mapping program has produced maps of the Moon, Mars, Venus, Miranda, and Phobos.

Topographic Mapping of the Moon: Photogrammetric aerial cameras were carried on the Apollo 15, 16, and 17 Lunar Orbiting Service Modules. These three missions provided the first photographic coverage of an extraterrestrial body that permitted full photogrammetric triangulation containing elevation information. Lunar photogrammetric triangulations were performed with the 1,250 photographs in 24 orbital paths of the Apollo dataset by two different agencies. The Defense Mapping Agency Aerospace Center (DMAAC) (Schimerman, 1973) used the orbital tracking data to constrain computations with Apollo 15 photographs. They later tied the Apollo 16 and 17 nets to the Apollo 15 net. The National Oceanic and Atmospheric Administration (NOAA) and the USGS (Doyle et al., 1977) performed a purely photogrammetric solution that obtained a simultaneous adjustment of 23,436 unknowns (coordinates of control points and parameters of camera stations) for the data from all three missions. In this net, 70 percent of all the adjusted control points and 74 percent of the elevations are accurate to better than 30 m, as indicated by the residual errors of the computation.

The DMAAC net was used to compile a series of Lunar Topographic Orthophotomaps at 1:250,000 scale by conventional photogrammetric methods. Until 1981, all lunar maps were made on a spherical datum. Wu (1981a, 1985) has proposed a new datum based on the known lunar gravity field in terms of spherical harmonics of fifth degree and fifth order, with the sixth-degree sectorial terms. Gravity coefficients used for the derivation of the datum were developed by Sjogren, who used Lunar

Orbiter 4 tracking data and laser ranging data (Ferrari et al., 1980). The NOAA/USGS net was converted to the proposed datum and has been used to compile an experimental topographic map (1:2,750,000 scale) of the part of the Moon covered by the Apollo photographs (Wu, 1981, 1985).

For special purposes such as geologic studies, topographic maps of the Moon were compiled at various scales from Apollo metric photographs (Figure 1). Several profiles were made from stereomodels. Standard errors of horizontal and vertical repeatability from the metric photography on the analytical stereoplotter were ± 7.4 m and ± 16.4 m, allowing a contour interval of 50 m to be used.

Topographic Mapping of Mars: Two global topographic maps of Mars have been compiled. The first was made from nonimaging topographic data from various scientific experiments of the Mariner 9 Mission. The map scale is 1:25,000,000 (Wu, 1975, 1978). The second map was made from nonimaging and imaging data of the Viking Mars Mission. The map scale is 1:15,000,000 (Wu et al., 1986). To control compilation of this map and the Mars 1:2,000,000-scale map series, a topographic control net was derived from a block of 1,160 Viking Orbiter images that provide stereoscopic coverage of the entire planet. The nominal resolution of these images is 750 to 1,000 m per pixel; they were taken from altitudes as high as 37,000 km above the Martian surface. The field-of-view of Viking Orbiter cameras is so narrow that stereoscopy only could be achieved by taking convergent photographs. The topographic control network was compiled by using the General Integrated Analytical Triangulation (GIANT) program of the USGS (Elassal et al., 1970).

The control net was originally compiled in two bands. The equatorial band extends from lat 30° N. to 30° S. A second band covers about 30° on both sides of the 120° and 300° meridians. The first effort produced 3,172 topographic control points. Residual errors in the adjustment are approximately 4 km horizontally and 750 m vertically (Wu and Scafer, 1984).

A supplemental net containing 446 Viking Orbiter images was derived to fill in the 30 percent of the planet not covered by the original two bands. The stereoscopic geometry in these areas is poor, resulting in residual errors of approximately 5 km horizontally and 800 m vertically. By using control points from the combined planetwide control network, Mars' topography is being systematically mapped at 1:2,000,000 scale. Figure 2 is an example of this mapping. A perspective view of part of the map area, controlled by digital elevation data is shown in Figure 3. A total of 140 topographic quadrangles of Mars in the 1:2,000,000-scale map series will be compiled.

Topographic Mapping of Venus: A global topographic map of Venus has been compiled by nonphotogrammetric methods, using radar altimetry data returned by Pioneer Venus (Pettengill et al., 1980). Venus' topography will be mapped in great detail with "radargrammetric" techniques by using stereoradar data from the Magellan Mission. Techniques of radargrammetry are discussed later in this paper.

Topographic Mapping of Miranda: In January 1986, the Imaging Science System (ISS) of Voyager 2 took a series of pictures of Uranus and its

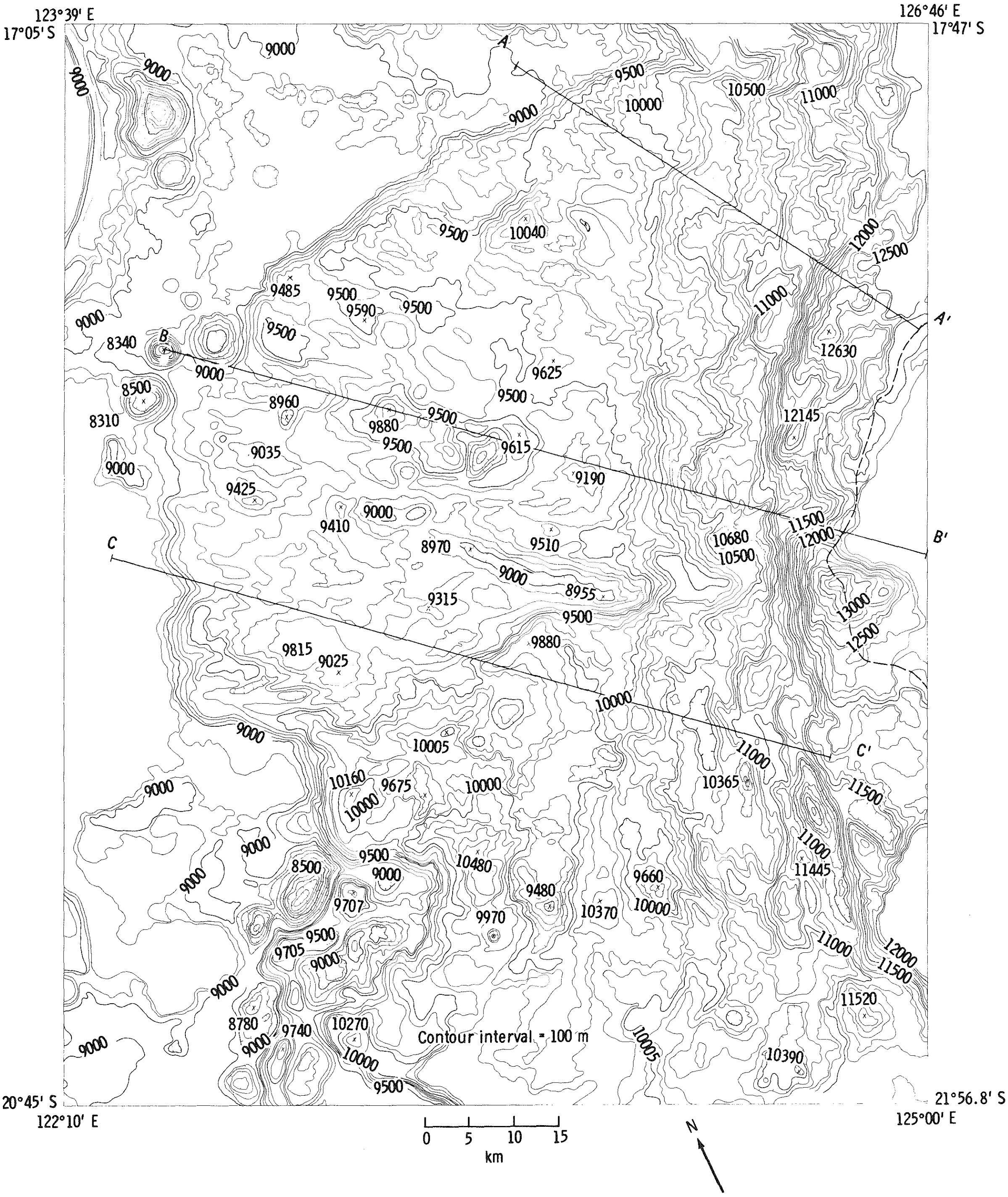
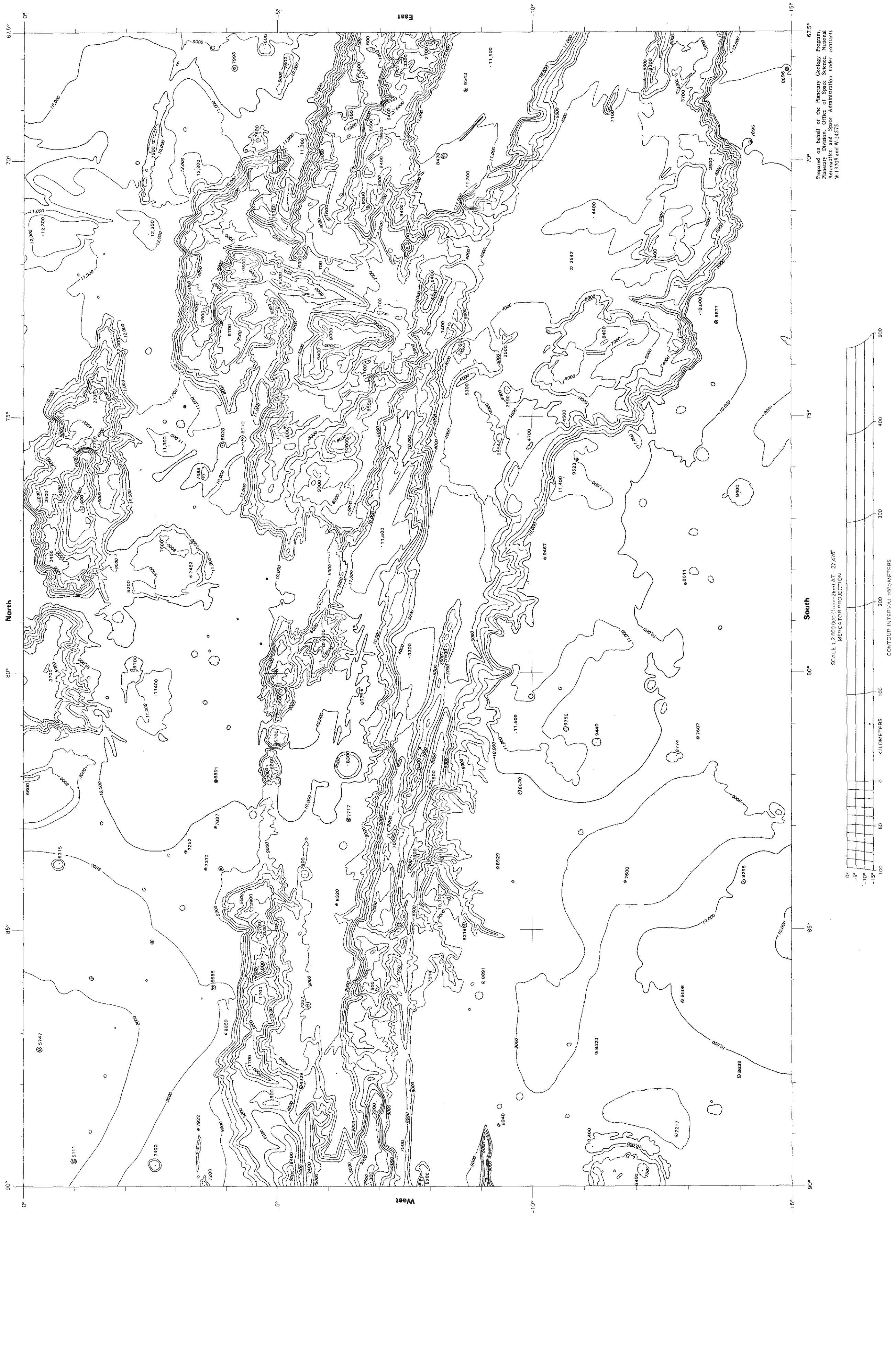


Figure 1 - Topographic map of landslide area of Tsiolkovsky crater on the Moon. Compilation scale 1:100,000; contour interval 100 m.



North
South
East
West
Prepared on behalf of the Planetary Geology Program, Planetary Division, Office of Space Science, National Aeronautics and Space Administration under contracts W 13709 and W 14575.
SCALE 1:2 000 000 (1mm=2km) AT -27.476°
MERCATOR PROJECTION
KILOMETERS
CONTOUR INTERVAL 1000 METERS

Figure 2 - Topographic map of Coprates Northwest quadrangle of Mars (U.S. Geological Survey, 1986), covering part of canyonlands of Valles Marineris. Contour interval 1 km This format is typical of Mars 1:2,000,000-scale map series. Contour interval 1 km, covering part of canyonlands of Valles Marineris. Compilation made on the AS-11AM analytical stereoplotter from 9 stereoscopic models from 11 Viking Orbiter photographs. Photographs have slant ranges of 17,400 to 33,700 km and tilt angles ranging from 16° to 43°. (Previous page)

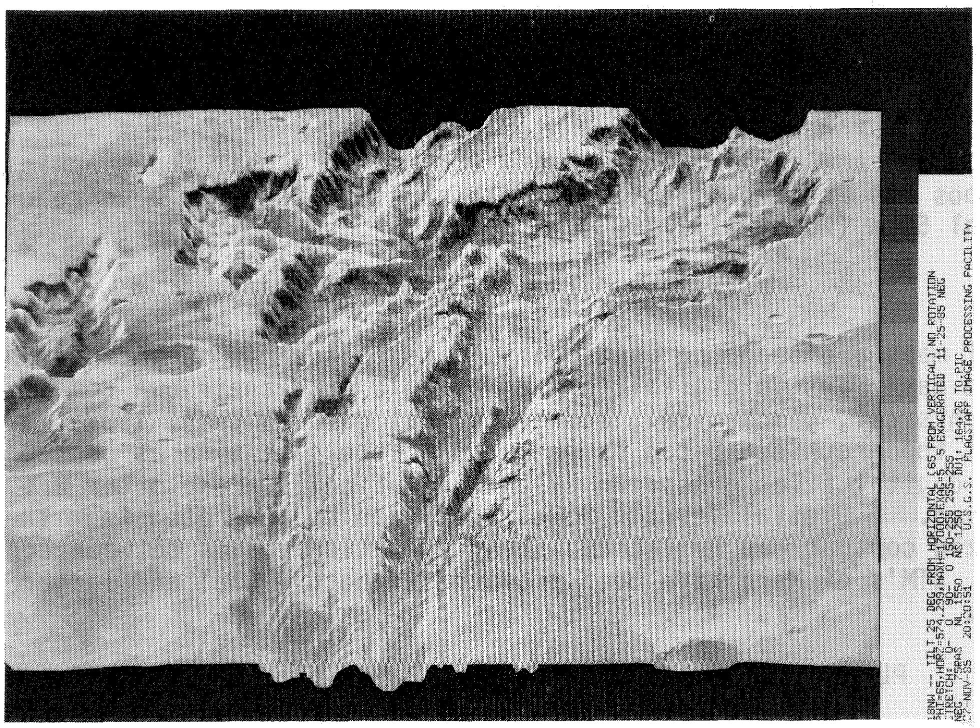


Figure 3 - Perspective view of small part of the canyonlands in the area of Coprates Northwest quadrangle shown in Figure 1, made with Viking Orbiter pictures 663A44, 663A42, and 613A61. Projection controlled by digital elevation data collected from map shown in Figure 1. View due east at angle of 25° from horizon. Vertical exaggeration 5 times.

five major satellites (Smith et al., 1986). The ISS consists of a wide-angle camera (200-mm focal length) and a narrow-angle camera (1,500-mm focal length). Each frame of the two cameras consists of 800 X 800 elements with a pixel size of 14 ˉm. Both cameras have a grid of 202 reseau marks. Calibration of reseau coordinates has an accuracy of better than 2 ˉm (Benesh and Jepson, 1978). Based on six stereoimages from the ISS narrow-angle camera, a topographic map was compiled of the southern hemisphere of Miranda, the smallest and innermost of Uranus' major satellites (Wu et al., 1987). For compilation from multiple-stereomodels, a control net was established from the six high-resolution pictures and three pictures from the wide-angle camera.

Although Miranda displays the most complex features in the Uranian system, other Uranian moons are also extensively cratered and faulted and are poorly understood. Compilation of topographic maps of all the major moons of Uranus in progress.

Topographic Mapping of Phobos: Using 67 high-resolution Viking Orbiter pictures ranging from 235 to 966 km, we have established a ground control network for Phobos, one of Mars' moons. Control points produced by the control network have a precision better than 30 m. A triaxial ellipsoid of Phobos was also modeled with semi-major axes; A = 12.7 km, B = 11.4 km, and semi-minor axis C = 9.9 km. A global topographic map of Phobos has been compiled at a scale of 1:100,000 with a contour interval 50 m (Wu et al., 1988).

PLANETARY DIGITAL TOPOGRAPHIC MAPS

Digital maps are becoming indispensible to planetary researchers who require base maps in digital form compatible with their own compilations of geophysical, geochemical, and geological data (Batson, 1987). A digital topographic map can be produced at the same time as contour maps if the digital files generated by the analytical stereoplotter are preserved. A Digital Terrain Model (DTM) can be generated from the digitized contour map by interpolating elevation values between contour lines. DTM's of Mars have been produced at both global and larger scales.

PLANETARY TOPOGRAPHIC MAPPING FROM FUTURE MISSIONS

Extensive planetary topographic mapping will be done in the next decade. Of the three approved missions (Galileo to the Jovian system, Magellan to Venus, and Mars Observer), Galileo has an imaging system capable of making the kinds of photogrammetric measurements that have been done in the past. Venus' topography will be compiled by using mainly altimetry data, but stereoradar data from the Magellan Mission will be used for photogrammetric compiliation by novel radargrammetric techniques. Altimetry data from Mars Observer will be important for revising and improving the existing control network, topographic datum, and topographic maps of the planet.

Venus: Topographic Mapping with Radargrammetry: Eighty percent of the surface of Venus will be mapped with synthetic aperture radar during the nominal 243-day lifetime of the Magellan mission. High-resolution radar images will provide data for planimetric mapping, and radar altimetry (spot size of 10-30 km, vertical resolution of about 15 m) will provide topographic measurements. Spacecraft tracking cannot be done with sufficient precision during the nominal mission to improve the currently adopted spherical figure to any appreciable extent. It is likely, however, that the mission will be extended well beyond 243 days, which will allow image mapping of the remaining 20 percent of the planet as well as gravity mapping and obtaining of stereoradar images that can be used to make topographic maps.

By means of radargrammetry, topographic measurements of surfaces are made from stereoscopic radar images, just as these measurements are made from optical stereoimages by photogrammetry. Conventional photographic images have a point-perspective geometry, whereas radar images have a lateral range and down-track horizontal distance geometry. Further comparisons of radargrammetry and photogrammetry are made by Wu et al. (1988); these authors also describe compilation software for stereoradar imagery that has been developed on the AS-11AM analytical stereoplotter of the USGS in Flagstaff, Arizona, and they discuss factors that affect mapping accuracy.

Figure 4 shows a contour map of Mt. Shasta generated from a stereomodel based on images from a SIR-B experiment, which used an L-band radar capable of providing images at multiple look angles ranging from 15° to 60°. The images from which the model was compiled had different look angles (29.5° and 60.1°) and different resolutions (28.5 m and 16.2 m, respectively). The repeatability of elevation measurement was 8 m, with an elevation residual of 55.4 m.

The geometric transformation between the image coordinates of range and azimuth (or squint) is well known (Blackwall, 1981), and it has been incorporated in software for the compilation of SAR images on the AS-11AM analytical stereoplotter (Jackson, 1985).

Topographic mapping using stereoradar images has been proven possible and is expected to be fully operational in time to utilize stereoscopic SAR images returned by Magellan. By that time it will also be possible to make contour maps based on digital stereoradar images.

Enhancement of Mars Topographic Maps With Data the From Mars Observer Mission: Mars Observer is scheduled for launch in 1992. One of its primary goals is to define the global topography and gravitational field of Mars. Topographic measurements will be made by radar altimetry. The anticipated measurement precision is 10-15 m for a nominal spot size of 2.5 km. The entire surface of the planet will be mapped at this resolution during a single Martian year (about 2 Earth years). A high-resolution imaging system operating simultaneously with the radar altimeter will be used to locate the radar profiles on existing Digital Image Models (DIM's) that were prepared with Viking Orbiter data.

The Mars Observer altimetry will be formatted as a Digital Terrain Model and will provide a dataset complementary to the photogrammetric compilations from Viking Orbiter. The regional accuracy of the Mars Observer data is expected to be much higher than that of existing topographic maps. The existing maps, on the other hand, discriminate topographic details at higher resolution than can be achieved with altimetry. Together, the two datasets may produce the most precise and comprehensive map ever made of an entire planet, including Earth.

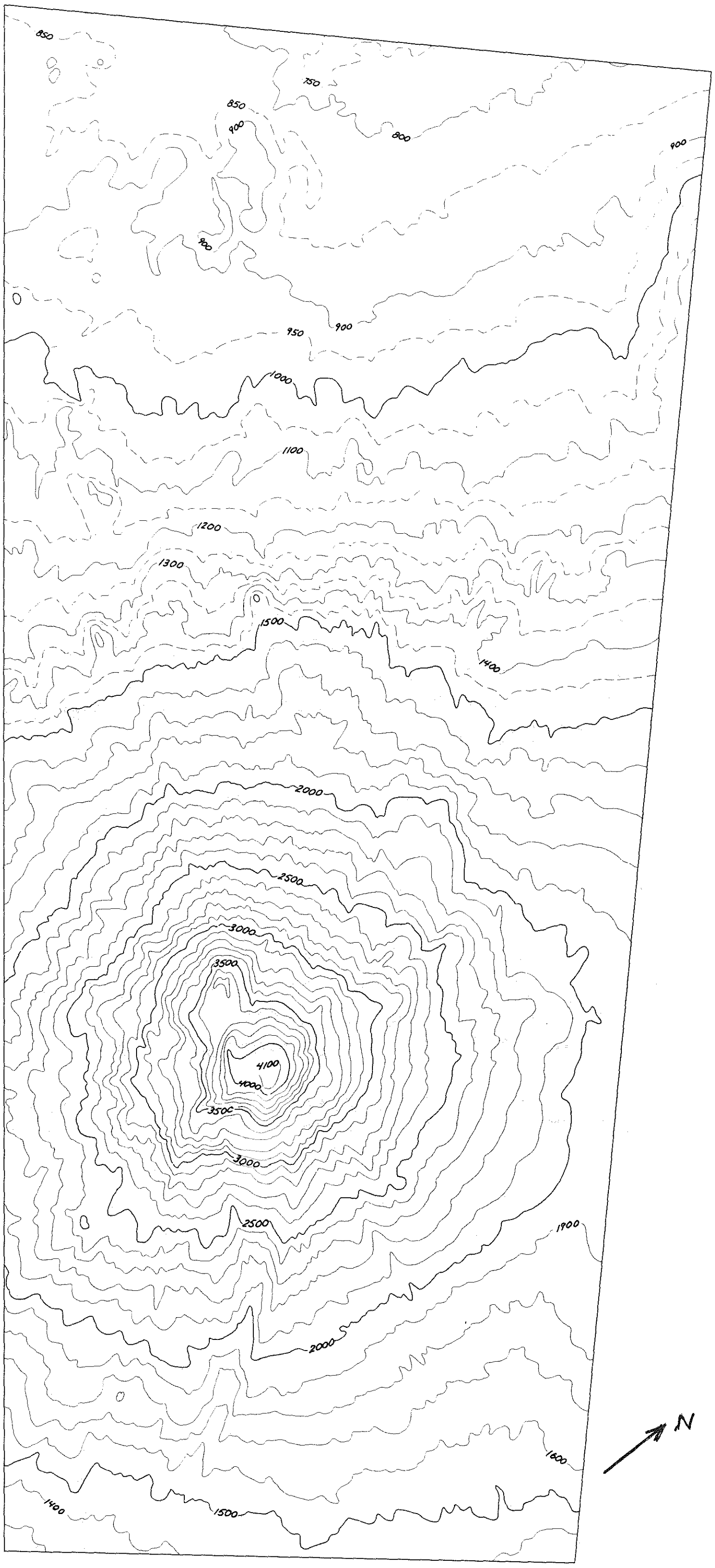


Figure 4 - Contour map of Mt. Shasta compiled from SIR-B radar images by using synthetic-aperture radar compilation system on AS-11AM analytical stereoplotter. Compilation scale 1:100,000. Contour interval 100 m;

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