TOPOGRAPHIC ATLAS OF MARS

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ABSTRACT:

Topographic Atlas of Mars is the publication of a book which describes developed mapping techniques and archives topographic products of Mars. Using topographic data from various scientific experiments of Mars missions and from Earth-based radar observations, topography of the entire Martian surface has been systematically mapped at various scales by the United States Geological Survey(USGS) in Flagstaff, Arizona. These topographic products are the first and will retain as the most comprehensive topographic maps of Mars. This book consists of six chapters as outlined in the Table of Contents. Chapter 1 briefly discuses Mars, Mars missions and mapping strategies. Chapter 2 defines the coordinate system of Mars and map projections used for mars mapping. Chapter 3 discusses the derivation of topographic datum of Mars. Chapter 4 discusses the Mars planetwide topographic control network. Chapter 5 describes special techniques developed for photogrammetric mapping of Mars using the Viking Orbiter images. Chapter 6 discusses nomenclature and users' guide of Mars maps. With these topographic products, mars elevation above and below the topographic datum are found to be 67% and 33%, respectively. The mean elevation is about 1.876 km above the datum.
The Table of Contents of the book is listed as in the following. This paper discusses only briefly of each of the six chapters.

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Book Size: 12" x 15"

Total number# of pages:	est. 180 pages
Text:	42 pages
Illustrations:	24 (17 line drawings, 6 black & white half-tone, and 1 color half-tone), est. 15 pages
Topographic Maps:	112 contour maps superimposed on half-tone image maps, 3 line-drawing maps, 3 color image maps (front and back cover) and 3 color line-drawing maps (attachment pocket), est. 117 pages
Tables:	6, est. 4 to 6 pages

1 . INTRODUCTION

Mars, one of our closest neighboring planets, is the fourth planet from the Sun revolving in an orbit between Earth and Jupiter. Mars has a mass of only one tenth of that of the Earth's and one seventh of the Earth's volume. The symbol for Mars is (o) represents a shield and spear (Glasstone, 1968).

Mars also has four seasons but has 687 days with 24 hours and 39.6 minutes per day in a solar year. Because of the seasonal changes, the polar caps and the bright areas and dark areas are the most prominent features on the Martian surface. Other prominent features include huge volcanic features and a long canyon complex. The bright areas of Mars which include both orange and yellowish brown areas cover about 70% of the Martian surface. This is the reason why the planet looks reddish and is therefore called the red planet. Mars has two moons, Phobos and Deimos, which are heavily cratered and irregular in shape.

The charting of the Martian surface started as early as 1840 by German astronomers W. Beer and J.H. Madler. The first series of maps of Mars were made by G. Ovanni Schiapaelli from his observations during the period from 1870 to 1879 (de Vacouleurs, 1965). He introduced linear markings called "canali" in the map. Since 1964, from spacecraft imaging data transmitted by mariner 4, Mariner 6, and Mariner 7, no linear network of canal-like features were observed on the martian surface. It was Mariner 9 (1971) and Viking (1976) Mars missions that had photographically covered the entire Martian surface and have accomplished a giant step toward the understanding of the red planet Mars. One of the accomplishments is that using topographic data from Mars missions and from Earth-based radar observations, topography of the entire Martian surface has been systematically mapped at various scales by the United States Geological Survey (USGS) in Flagstaff, Arizona.

Topographic maps of Mars provide a quantitative representation of landform and relief of the Martian surface and lead to a better understanding of geologic and tectonic histories of Mars. Topographic mapping of Mars, however, differs in many ways from the mapping of Earth. It involves solving unprecedented problems: the absence of ocean to provide a zero-elevation reference surface, the lack of precise ground control, methods of data acquisition, or characteristics of data, and so forth. These unconventional factors require new approaches and the development of new mapping techniques.

As Mars has no seas hence no sea level, the most appropriate definition for its topographic datum, the zero-elevation surface, is a 6.1-millibar pressure surface (Wu, 1981) with a gravity field represented by fourth-degree and fourth-order spherical harmonics (Jordan and Lorell, 1975, Christensen, 1975.)

Topographic data used for mars topographic mapping include imaging and non-imaging remotely sensed data. Imaging data are Mars images taken by the two narrow-angle cameras on board of the two Viking missions. Despite the extremely narrow field-of-view of the Viking Orbiter images, special photogrammetric techniques have been developed enabling stereomodels to be established for map compilation on AS11-AM analytical stereoplotters (Wu et al,. 1982). Using these techniques, a total of 140 contour maps of 1:2,000,000-scale with contour interval of 1 km has been compiled and covers the entire Martian surface.

Non-imaging topographic data include the Ultraviolet Spectrometer(UVS), the Infrared Radiometer(IRR), and the Infrared Interferometer Spectrometer(IRIS) on board spacecraft of Mariner 9, and the S-band radio occultation measurements, from both Mariner 9 and Viking missions. Earth-based radar observations of Mars have been used and also played an important role in Mars topographic mapping.

From 1,157 high-altitude Viking Orbiter images together with occultation measurements and Earth-based radar data, a planetwide topographic control net was established and has produced 4,502 control points for the control of systematically mapping of the entire Martian surface (Wu and Schafer,1984).

Mars small-scale topographic maps , i. e., 1:5,000,000, 1:15,000,000, and 1:25,000,000 were compiled with the combination of topographic data extracted from the 1:2,000,000-scale contour maps, and the non-imaging topographic data including Earth-based radar observations of Mars as described above.

By digitizing 1:2,000,000-scale contour maps, a Mars Terrain Model (MDTM) has been derived with a resolution of 1/59.226 degree, exactly 1 km per pixel at the equator.

Despite the coarse data from limited data sources, these topographic products are results of series of Mars projects and are the first comprehensive topographic maps.

2. MARS TOPOGRAPHIC DATA SOURCES FROM MARINER 9 AND VIKING MISSIONS

Topographic data used for Mars topographic mapping are derived from remotely sensed data of various devices of experiments from Mariner 9 and Viking missions. For example, two television cameras on board the Mariner 9 spacecraft photographed the entire Martian surface (Masursky et al., 1970). But it was the two Viking Orbiter missions that sent back almost 60,000 images of Mars to Earth, made it possible to systematically map Mars' topography in great detail. Scientific experiments, which have significance to the topographic data, imaging or non-imaging, are briefly described in the following two sections.

2.1. Imaging Data

The primary goal of Mariner 9 was to photographically map the planet Mars. More than 7,300 images of Mars were taken by the two cameras (wide- and narrow-angle cameras). But it is the 60,000 images of Mars, which were taken by the Visual Imaging subsystem (VIS) on the two Viking Orbiters, to have been used for the control network and for stereoscopically compiling Mars topography. The VIS on each of the two Viking Orbiters consists of two identical vidicon cameras with nominal focal lengths of 475 mm. Each image consists of 1,056 lines (along y-axis) with 1,182 samples (along x-axis) in each line, and thus contains approximately 1,200,000 picture elements. At a 12.494 mm x 14.021 mm format, each pixel is 11.8 micrometers square. The field of view is 1.538 x 1.592 degrees, or 2.286 degrees diagonally. A resau grid consisting of 103 resau marks is incorporated in each camera. The resau marks are 36 micrometers, or 3.1 pixels, on one side. The calibrated coordinates of resau marks are known to better than 2 micrometers. Geometric distortion are less than 3 pixels at the center and increase outward. After the IPL decalibration is made to the Viking Orbiter images, the r.m.s. errors are reduced drastically to less than 2 μm (Ruiz,1976). Therefore, optical distortion can be ignored for images processed by IPL's dicalibration software. At the altitude of 1,500 km, the ground coverage of a vertical photograph is about 39.6 x 44.4 km. Each pixel is 37.5 m square.

2.2 Non-imaging Data

Non-imaging topographic data, such as spectroscopic sensors and Earth-based radar, can contribute topographic mapping, for example, during 349 days in Martian orbit, the instruments for five of the six experiments (Masursky et al., 1970) of Mariner 9 provided measurements of the surface and atmosphere of Mars. Most of the results of these experiments were used to compile the early version contour maps of Mars (Wu, 1975, 1978). The following is a brief description for each of these data sources.

2.2.1 S-band Radio occultation: The S-band radio occultation experiments were included in all Mariner missions, including the Mariner 9 (Kliore et al., 1973). The radius of Mars can be determined at the instant of the spacecraft orbital occultation at both entry and exit by recording the time immediately before and immediately after an occultation (Kliore et al., 1972). A total of 256 usable occultation points from Mariner 9 mission were used. The two Viking missions added about another 155 points that make occultation points having a wide distribution over the entire Martian surface. The uncertainty of the occultation measurements used range from 0.25 km to 1.10 km (Kliore et al., 1973; Christensen, 1975), therefore, they were used as one source of primary controls for the derivation of the Mars planetwide control network.

2.2.2 Ultraviolet Spectrometer (UVS): The major objectives of the UVS experiment were to measure structure, composition, and pressure of the Martian atmosphere (Barth et al., 1972). The local pressure at the surface can thus be converted to topographic values (Barth and Hord, 1971). The UVS experiment provided about measurements of elevation along 39 orbital nadir tracks, covering 60°S to 45°N latitudes. The measurement precision depends on the weather. Data were used only for the early version of the 1:25,000,000-scale global topographic map of Mars (Wu, 1975).

2.2.3 Infrared Interferometer spectrometer (IRIS) and Infrared Radiometer (IRR): The infrared interferometer spectrometer was used to infer the Martian atmosphere and surface which include the temperature for a vertical temperature structure. It also provides topographic information through the absorption of certain bands of carbon dioxide. The absolute accuracy is about 1 km (Herr and Pimentel, 1969; Hanel, et al., 1970; Hanel et al., 1972). The infrared radiometer is used to infer the thermal properties of the Marian surface (Chase et al., 1972). The data can also be used to compile a temperature map which can be correlated with topographic variations (Cunningham and Schumeier, 1969). There are about 4,600 elevation points provided from the infrared experiment also observed along the tracks of Mariner 9 in the same regions covered by the UVS experiment, covering the planet Mars from 65° south latitude to 40°north (Wu, 1975).

2.3. Earth Based Radar Data

Radar observation of Mars were initiated in 1963 (Goldstein and Gillmore, 1963). Elevation on the Martian surface are calculated from signal time delay. In other words, variations in travel time to and from Mars are associated with the topographic relief on the Martian surface. The resolution of the observations can be as small as 8 km and the precision of the height measurements ranges from 75 m to 200 m (Pattenngill et al., 1971, 1973; Downs et al., 1971, 1973; Goldstein et al., 1970). However this precision is simply a direct translation from the time measurements of the observations.

Along with sensor data from Mariner 9 , more than 15,000 data points on Mars topography observed from Goldstone Observatory, California and Haystack observatory, Massachusetts, were used in this experiment for compiling both the early and the current versions of contour maps of Mars. All the information of Earth-based radar data used can be found in Wu's publication (Wu, 1975). For local relief, the radar data seem to be very reliable but for global topography, the ephemeris and the figure of Mars used as the datum are important factor for radar observations.

More than 2,700 radar points from the oppositions of 1967, 1969, and 1971 at Haystack Observatory, and more than 13,000 points from the oppositions of 1969,1971, and 1973 at Goldstone Observed were used for the Mars project. The coverage of these points from these two observatories is approximately from south 22.5° latitude to north 25° latitude. the exact location of each year's opposition of Haystack and Goldstone observatories are shown in Wu's publication (Wu, 1975)

3. MARS COORDINATE SYSTEM AND MAP PROJECTIONS

3.1 Mars Coordinate System

In 1972 the Mariner 9 Geodesy/Cartography Working Group of the Television Team selected the Martian zero-meridian to pass through a particular small crater which is approximately at the center of a larger crater. The large crater was then named Airy (in honor of the late director of the Greenwich observatory, Sir George Biddell Airy, who installed a transit instrument to be used to define the prime meridian on the Earth in 1884) and the small crater Airy-0. The longitudes of this new system increases to the west. The Airy-0 is located at -5.19° south of the Martian equator (de Vaucouleure et al., 1973)

Reports from the IAU Working Group on Cartography Coordinates and Rotational elements of the planets and Satellites give the best current solutions to define the Mars north pole an prime meridian by $\alpha_.$ (right ascension), and $\delta_.$ (declination), and W (hour angle), respectively. The hour angle is measured from Q, the node defined by the intersection of the J2000 Earth equator and the Mars equator, along the Mars equator to the Mars prime meridian. The right ascension, declination and hour angle of Mars are computed as the following:

$$\alpha\ (2000.0) = 317.681° - 0.108°\ T$$

$$\delta\ (2000.0) = 52.886° - 0.061°\ T$$

$$W\ (2000.0) = 176.868° + 350.891983°\ d$$

Where T is measured in centuries and d is measured in days from JD 2451545.0 TDB

For the computation of map projection, the adopted reference spheroid has an equatorial radius A = 3,393.4 km and a polar radius of B = 3.375.8 km. This yields a Martian flattening of 0.0052 or 1/192 and an eccentricity (e) of 0.101715. The Working Group also adopted the aerographic coordinate system to be used for all Mariner 9, later Viking, and map products. The origin of the coordinate system is at the center of mass of Mars.

3.2 Map Projections

For Mars topographic mapping, three conformal map projections (Mercator, Lambert, and Polar Stereographic) are used. The Mercator projection is used for equatorial band,, Lambert for medium latitudes, and polar stereographic for the polar regions. For large-scale maps, 1:1,000,000 or larger, the Transverse Mercator is used. Sinusoidal equal-area projection is occasionally used, mainly for global-scale digital maps.

3.2.1 Mercator Conformal Projection: For the Mercator projection, the x and y coordinate axes are straight lines and the origin of y-coordinates is at the equator (Thomas, 1964). The projected scales vary depending upon the latitude of the point projected. It is 1:1 along the equator and becomes greater for greater latitudes. The Mercator projection is used between the 65° north and 65° south of latitude for the 1:25,000,000-scale global map and between 30° north and 30° south of latitude for both - and 1:2,000,000-scale series of Mars maps. For the 1:25,000,000-scale map , the scale is 1:10,610,713 at the 65° of latitude, greater than twice that at the equator.

3.2.2 Lambert Conformal Conic Projection: In the Lambert conformal conic projection, the projected parallels (latitudes) are arcs of concentric circles with radii which are their corresponding projected meridians. the common center is also intersected by the projected meridians (Thomas, 1964, Richardus and Adler, 1972). The meridian of each quadrangle serves as its y-axis, and the intersection of the y-axis and its lower parallel (latitude) serves as the origin. To minimize scale distortion, two standard parallels are used. This allows the latitude difference between the two standard parallels to be 23.34° to be two-thirds of the latitude difference between the two boundaries, so that scale errors are more uniformly distributed. The scale is true only along the two standard parallels.

It should be noted here that the scale of so-called 1:5,000,000 maps is not exactly 1:5,000,000. The scale of the quadrangles is set to match the scale at the lower boundary latitude (30°) of the Lambert projection with the scale at the upper boundary latitude (30°) of the Mercator quadrangles which is already distorted with a scale ratio (with the equator) of 0.867151. In other words, the scale at the latitude 30° at the upper boundary of the Mercator projection, is no longer 1:5,000,000, rather, it is 1:4,335,753.

3.2.3 Polar Stereographic Conformal Projection: The polar stereographic projection is a special case of the Lambert projection with only one standard parallel being the point at the pole. Therefore, the meridians are straight lines radiating from a central point which is the pole and the parallels are concentric circle about this central point (Thomas, 1964). The polar stereographic projection is used for the polar regions from ±55° to the poles for the 1:25,000,000- and 1:15,000,000-scale maps. and from ±65° to the poles for 1:5,000,000-scale maps. The scale of the two polar quadrangles, MC-1 and MC-2, is determined by making the scale of latitude 65° to be the same scale as latitude 65° in the Lambert projections.

3.2.4 Sinusoidal Equal-Area Projection: The Sinusoidal is an equal-area projection, i.e., true for area scale in the map. It is used for global digital maps of Mars. All of the parallels are straight lines and the meridians are sinusoidal (sine curves.)

4. TOPOGRAPHIC DATUM OF MARS

The purpose of planetary topographic mapping is to provide topographic information for the support of mission planning and operation, and for geologic and other scientific studies of planets, it is vitally important that elevations be closely related to actual morphologies on the planetary surface such as those of lava flows and channel slopes. For instance, Mars has no seas and hence on sea water, it is not possible to use a sea-level reference for its topographic datum. The most appropriate method is to define a datum on the basis of Mars' gravity field. This gravity potential surface is not only a physical figure of mars, but it is also a long-range planning for accommodating high-resolution (1 - 2 km) and high-precision (1 m) topographic data from future Mars missions.

4.1 Gravity field of Mars

Because the gravity field of Mars is rough, a large number of coefficients is required in the spheric harmonic representation of the gravity field. But, Jordan and Lorell (1972) discovered that high-degree spherical harmonics are not stable and only the low-degree harmonics have demonstrated stability, especially those coefficients of the fourth degree. Therefore, the fourth-order and fourth-degree spherical harmonics derived for the gravity potential surface are used for computing elevations on the Marian surface. Incidently, a fourth-order and forth-degree spheric expansion had been considered to be used for representing the world-wide gravitational potential of the Earth when disagreement was found between both the northern and southern hemispheres (Utila, 1962a, 1962b).

The fourth-degree and fourth-order gravity coefficients of Mars are: J2=19.65, J3=0.36, J4=-0.29, C22=-0.548, S22=0.31, C31=-0.48, C32=-0.55, C33=0.048, S31=0.26, S32=0.026, S33=0.035. Values were obtained from the results of the celestial mechanics experiment of Mariner 9 (Jordan and Lorell, 1975). In the spheric harmonics expression, the associated Legendre polynomials are used and the mean radius of Mars is 3,382.946 km which was obtained by fitting the 6.1-millibar occultation pressure data from Mariner 9. Detail derivation of the spheric harmonics is discussed in Wu's publication (Wu, 1975).

4.2 The Figure of Mars

For many years, by optical measurements, astronomers observed a large flattening value of about 0.011 for Mars (Dollfus, 1972). However, by dynamic measurements from observations of the two satellites of Mars, a value of approximately 0.0052 was obtained. The radio occultation data from Mariner 9 indicated that the average terrain elevation in the northern hemisphere is about 3 to 4 km lower than that in the southern hemisphere. This mans that the northern hemisphere is closer to the center of mass of mars and Mars is also asymmetric in the north-south direction (Kliore, et al., 1972, 1973), therefore an oblate spheroid is not adequate to represent the planet.

Using the fourth-order and fourth- degree gravity coefficients and the mean radius of the 6.1-millibar pressure surface, a triaxial ellipsoid of Mars can be obtained to geometrically establish the topographic datum based on the gravity field of Mars (Christensen,1975), which are: A = 3,394.6 km, B = 3,393.3 km, C= 3,376.3 km, θ = 105°. These results confirm the Mars dynamic flattening of 0.0052 which was arrived in the early days by observing the two satellites of Mars.

4.3 Topographic Datum of Mars

The radius of the Mars mean sphere has a 6.1-millibar pressure (Christensen, 1975). As C.A. Berth suggested that a meaningful normalization on Mars is to choose the zero altitude at the triple-point of water (6.105 millibar). The radius of 6.1 millibar pressure surface is 3,382.946 km. Therefore, the Mars topographic datum is defined by equations derived in Wu's publication (Wu, 1975.)

5. PLANETOID TOPOGRAPHIC CONTROL NETWORK OF MARS

Using high-altitude Viking Orbiter images, the United States Geological Survey in Flagstaff has established a Mars planetwide control network by analytical aerotriangulation (using the USGS GIANT program.) Primary controls used for the adjustment include: (1) camera positions and orientations derived from the tracking data of Viking missions; (2) occultation measurements from the S-band radio experiment on both Mariner 9 and Viking missions (Kliore, et al, 1970, 1972, 1973); (3) elevation derived from Earth-based radar observations of Mars (Downs, et al, 1971, 1973, 1975; Goldstein, et al, 1970); and (4) horizontal coordinates from the control network by davies (Davies et al, 1978). This control network not only provides control for systematic mapping topography of Mars, but also valuable for: (1) improving the horizontal locations of occultation points on both the Mariner 9 and Viking missions; (2) calibrating locations of earth-based radar profiles; (3) improving elevations of Davies horizontal control network; and (4) adjusting the internal inconsistency of camera positions and orientations. In fact, the adjusted internal consistency of camera stations is the only means by which the extreme narrow field-of-view of Viking images can be used to establish stereomodels on the analytical stereoplotters for photogrammetric compilation. The adjusted camera parameters have been used to enhance the SEDR data to be called "Wu's Version" in the SPICE file.

The GIANT program uses an interactive least-square technique which requires initial approximation for each of unknown parameters. All parameters are treated as weighted parameters, ranging from known to unknown. This is particularly helpful for the Mars control network since we don't have good ground control points except occultation points and radar observations with limited precision. Using SEDR data, we can enforce camera positions and orientations from SEDR data.

5.1 Preprocess of Image Data:

A total of 4,502 control points has been produced from 1,157 Viking orbiter images. Including images used for stereocompilation on plotters, more than 3,000 Viking Orbiter images were digitally processed. Each control point appears on from 2 up to 13 images. More than 20,000 image points were measured. More than 90% of the 1,157 images are high-altitude ranging from 21,500 to 33,500 km above the Martian surface. Pixel resolution ranges from 500 to 850 m. The ground coverage of images ranges from about 520 x 610 km to 880 x 1,000 km. All images were geometrically and radiometrically corrected. The pixel size is 50 micrometers on Optronics Photowrite devices. The number of control points range from 7 to 70 with an average of 40 points for each quad. all selected points were marked using the Wild PUG 4 and measured three times on the Mann 422 Comparator. Applying a second-degree polynomial using measurements of 13 resau marks, residuals of distortions are about one-half pixel at the original format which is 11.8 micrometers.

5.2 Block Adjustment

The Mars control net work was carried out in two phases. Phase 1 consists of two interconnected bands, equatorial and polar, covering about 70% of the Martian surface and have produced 3,172 points from 715 Viking Orbiter images. Phase 2 filled in areas of the 30% of the Martian surface with 442 additional Viking Orbiter images. These four fill-in single-blocks are tied to the control net of phase 1 and have produced 1,330 additional control points of Mars.

Three input files are required for the block adjustment. The image file consists of all measured photo coordinates. The frame file includes three rotational and three positional components of each camera derived from the Viking Orbiter parameters, the SEDR data. SEDR is an acronym for Supplementary Experiment Data Record, which is a file containing information about conditions and geometry under which a Viking image was taken. The ground file includes geodetic coordinates of those points which are used for primary ground controls such as occultation measurements and Earth-based radar observations of Mars. Different weights are assigned to the controls depending on their reliabilities. There are 256 and 155 usable occultation points respectively from the Mariner 9 and Viking missions scattered over the entire Martian surface. Their uncertainties rang from 0.5 to 2.1 km (Kliore et al., 1973; Christensen, 1975). The precision of radar height measurements ranges from 75 to 200 m. About 1,000 Goldstone radar points were used.

Block adjustments were run on a VAX-750 computer. The output data include longitude, latitude and elevation (referring to the datum) of all ground points and the six adjusted camera components of images.

Residuals of the produced control points are about 4 minutes and 800 m respectively for the horizontal and vertical coordinates. Camera positions and orientations have been adjusted for the internal consistency for the enhancement of the SEDR data and for computing stereomodel parameters on the stereo analytical plotters, therefore enables the accurate compilation of the Mars 1:2,000,000-scale series of topographic maps.

6. TOPOGRAPHIC MAPPING OF MARS

With the establishment the planetoid control network, using Viking Orbiter images and topographic data from various scientific experiments of Mariner 9 and Viking missions, the USGS's Branch of Astrogeology (Flagstaff) has systematically mapped topography of the entire Martian surface at four different scales, i.e., 1:2,000,000, 1:5,000,000. 1:15,000,000 and 1:25,000,000. If high-resolution images are available, prominent features are compiled at larger-scale special maps (1:1,000,000 to 1:500.000). In addition a digital terrain model (DTM) of Mars has been derived. Topographic mapping of Mars, however, involves solving unprecedent problems and, requires new approaches and the development of new methodologies for handling unconventional data.

6.1 Mars 1:2,000,000-scale Series of Topographic Maps

The 1:2,000,000-scale series of topographic maps were compiled primarily by stereophotogrammetric methods using medium-range resolution of images taken at altitudes of 14,000 to 24,000 km. Because the extremely narrow field-of-view of the Viking cameras (long focal-length with very small image-format) and small base-to-height ratios between conjugate images, special techniques were developed for the photogrammetric compilation. One of the special photogrammetric techniques is to use adjusted SEDR data from the GIANT block adjustment of the Planetary control network to compute model orientation-parameters for setting stereomodels on the AP/C or AS-11A analytical stereoplotters (Wu et al,. 1982)

There are 140 quadrangles of 1:2,000,000-scale with 64 sheets between ±°30° of latitudes essentially 4 sheets within each of the 16 1:5,000,000-scale maps in the equatorial belt. All maps with the equatorial belt use the Mercator projection with true scale at the latitude ±27.476°. Each map covers an area of 22.5° (longitude) by 15° (latitude) on the Martian surface. the other 76 maps including 56 of the medium latitudes (±30° - ±65°) use Lambert conformal projection and 20 of the two polar regions (±65d -± 90°) use polar stereographic project. Maps with Lambert projection have true scales at latitudes of 35.83° and 59.17°. Stereomodels on the analytical plotters range from 2 to 16 for the compilation of each quad with an average of 8 stereomodels each. A total of more than 1,100 stereomodels were compiled for the 1:2,000,000-scale series of maps. Maps have a contour interval of 1 km. Map elevations are referred to the Mars topographic datum.

Factors that limited the accuracy of compilation include low-resolution (800 to 1,000 m/pixel) of high-altitude photography, the very narrow field-of-view of the Viking camera , weak model geometry (i.e., small base-to-height ratios) and the presence of dust and haze in the Martian atmosphere. However, at an altitude of 1,500 km, the ground resolution is about 37.5 m. with low-sun-angle images, standard errors or repeatability in the elevation measurements are small, ranging from 12.7 to 22.2 m. The maximum S.E. from images of the same condition is 34 m. In general, maps of the equatorial belt have a precision of ±1 km, and maps of the two polar regions have ±1.5 km due to the lack of stereocoverages.

6.2 Mars 1:5,000,000-scale Series of Topographic Maps:

The 1:5,000,000-scale topographic maps cover the entire Martian surface with 30 maps. There are 16 maps (MC-8 - MC-23) covering the equatorial belt from +30° to -30° of latitudes with each having a coverage of 45° lat by 30° lon using the Mercator projection. There are 12 maps (MC-2 - MC-24 & MC-24 -MC-29) covering from ±30° to ±65° of latitudes with each map having a coverage of 35° lat and 60° lon using Lambert conformal projection. The two polar regions from ±65° to ±90° are covered by two maps with polar stereographic projection (MC-1 & MC-30). The current version of this series of maps was compiled with topographic data extracted from all of the 140 quads of 1:2,000,000-scale contour maps and with additional remote sensed data including ground-based data.

6.3 Mars Global Topographic Maps

There are two global maps of Mars, 1:15,000,000 and 1:25,000,000 scales. Both cover the entire Martian surface. The 1:15,000,000-scale maps consists of three sheets: the Western hemisphere from lon 0° to 180°w, the Eastern hemisphere from lon 180° to 360°W, and the two polar regions above lat 55°. Both the Western and the Eastern sheets have the Mercator projection and cover latitudes from 57° to -57°, whereas the two polar regions have a polar stereographic projection.

The 1:25,000,000-scale global topographic map covers the entire Martian surface by one sheet with the Mercator projection from lat +65° to -65° and the polar stereographic projection covering lat above ±65°. Both scales of global maps were compiled from topographic data extracted from the stereoscopically compiled 140 quads of 1:2,000,000-scale contour maps. In addition, occultation data and Earth-based radar data were included. Maps have a contour interval of 1 km. Elevations refer to the Mars topographic datum. Elevation precision is about ±1 km in the equatorial band and ±1.5 km in the two polar regions.

6.4 Special Topographic Maps of Mars

Using the developed special photogrammetric techniques with available high-resolution Viking Orbiter images of Mars, topographic maps of features of geologic interest and of areas that are the subject of future mission planning are compiled at larger scales, 1:1,000,000 or 1:500,000. Completed special maps include those of Olympus Mons (Wu et al., 1981), Arsia Mons, Mars Canyonlad and others. For the compilation of larger-scale maps, a separate control network is established for each compilation. For example, a control net with 316 control points of Olumpus Mons was established from a block of 103 Viking Orbiter images. It took just about 100 stereomodels to compile the topographic map at a scale of 1:1,000,000 with a contour interval of 200 m.

Contour maps of the two Viking Lander areas were compiled by applying special techniques for the use of Mars surface images taken by the two fixed-base facsimile cameras on each of the two Viking landers. Pictures reconstructed from data of the facsimile cameras represent a portion of a spherical surface. in order to use them for stereocompilation, the panoramic images were converted to the equivalent of a frame pictures using a gnomonic projection (wu, 1984). Contour maps were then compiled on analytical plotters for the use of guidelines of the surface activities of the Viking landers during the Viking missions. Maps were compiled at a scale of 1:10 with a contour interval of 1 cm.

Using 64 high-resolution and 15 low-resolution images of Phobos, one of the two Martian moons, a geodetic control net with 536 control points was established. From these control points, Phobos has radii ranging from 8.523 to 13.950 km. Also a triaxial ellipsoid figure of Phobos has ben modeled with semi-major axes A = 12.747 km and B = 12.321 km, and the semi-minor axis C = 9.929 km. With the control network, a global topographic map (1:100,000) and a larger-scale topographic map (1:25,000) of Phobos were compiled with contour intervals of 500 m and 20 m respectively.

6.5 Mars Digital Terrain Model (DTM)

Mars DTM was derived as a by-product of the Mars topographic mapping and was produced by digitizing contour maps of Mars. There are two versions of Mars DTM's, a moderate resolution from the 1:15,000,000-scale topographic maps, and a high resolution from 1:2,000,000-scale topographic maps. The Mars DTM's use Sinusoidal equal-area projection and have been transcribed to optical disk (CD-RAM Volume 7 - V02007) of the planetary data system. By using the Mars DTM, a color-coded global map of Mars' topography was generated in both the Sinusoidal equal-area projection and the Mercator projection.

6.6 Quantitative Analyses of Mars Topography

By using contour maps and the DTM, we have made quantitative analyses of Mars topography that Mars elevations above and below the topographic datum are found to be 67% and 33% , respectively. The average elevation of the western hemisphere (0° - 180°) is about 0.993 km higher than the eastern hemisphere (180° - 360°); also, the southern hemisphere averages about 3.191 km higher than the northern hemisphere (due to a shift of Mars center of mass by approximately 3.4 km to the north of the center of figure.) The mean elevation is about 1.876 km above the datum. The volume of the western hemispheres about 72 million cubic km greater than the eastern, and the southern hemisphere is about 244 million cubic km greater than the northern. The total global volume of Mars is about 163.2 billion cubic km.

7. DISCUSSION

Because Mars missions were not specifically planned for making three-dimensional photogrammetric measurements, these data do not fulfill mapping requirements and therefore attribute in poor precision of topographic mapping. For example, by using Viking Orbiter images of Mars, compilation is limited by factors such as: low-resolution photography, very narrow field-of-view of the camera, weak geometry (i.e., small base-to-height-ratios), the presence of haze and mist in the Martian atmosphere, and differences in the direction of illumination in pairs of stereo-images. In any rate, these topographic products of Mars are the first and will retain as the most comprehensive topographic maps until the next enhancement using updated topographic data from future Mars Missions.

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