ANALYTICAL SYSTEMS FOR DATA REDUCTION WITH IMAGERY OF EXTRATERRESTRIAL BODIES

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ABSTRACT

Imagery of extraterrestrial bodies has been, and in the future will continue to be, acquired by a wide variety of sensors. Examples of such images are Hasselblad, metric and panoramic camera images of the Moon, vidicon and facsimile camera images of Mars, and radar images of Venus, etc. Topographic information of extraterrestrial bodies is derived using these images on various analytical stereoplotters, AP/C, AS-11A, and AS-11B-1 as well as using pure analytical solutions. Because of the extremely narrow field-of-view of the Viking vidicon cameras, special techniques were developed for the photogrammetric compilation from stereoscopic photographs of Mars from the two Viking Orbiter spacecraft. Using imagery taken by facsimile cameras, the most accurate methods of mapping the two Viking Lander areas were to make all image conversions and corrections in real time on an analytical stereoplotter. Using panoramic photography of the Moon, lunar maps were compiled using special software programs on the analytical plotters. Technical derivation and software development are reviewed. Development of stereo radar compilation using analytical stereoplotters is also discussed.

I. INTRODUCTION

Topographic mapping of extraterrestrial bodies differs in many ways from the mapping of Earth. It involves solving many unprecedented problems: the lack of precise ground controls, the absence of oceans to provide a zero-elevation reference surface, and methods of data acquisition, etc. These unconventional factors require the development of new methodologies and new equipment. Because of the fact that most of the planetary missions were not specifically planned for making three-dimensional photogrammetric measurements, stereo models, in many cases, can be constructed only by pictures that were taken from camera stations in different orbits. As a consequence, the pictures of the stereo models have different flight heights, a different appearance of the same surface area caused by shadowing effects from different sun angles, and very unusual model geometry. However, in some cases, high-quality cameras capable of making reliable measurements for topographic mapping were carried aboard orbiting spacecraft such as the Apollo 15, 16, and 17 missions. In fact, the photogrammetric system installed in the scientific instrument module bay of the Apollo service module (metric-, panoramic-, and stellar-camera and a laser altimeter) provide almost everything that a photogrammtrist could want.

Remote sensing data, imaging or nonimaging, from devices using a broad spectrum of wavelengths play an important role in planetary topographic mapping. This paper discusses analytical systems for map compilation and data reduction with planetary images from various planetary missions, Apollo, Mariner, and Viking Mars, as well as the planned Venus Radar Mapper. Planetary images include those that have been and those that will be acquired by various cameras, metric, panoramic, vidicon cameras as well as other remote sensing devices such as the synthetic aperture radar systems.

II. PHOTOGRAMMETRIC APPLICATION OF PLANETARY IMAGES

Planetary imagery applicable for photogrammetric compilation includes pictures of Mars taken by vidicon television cameras from both Mariner 9 and Viking missions and by facsimile cameras also from Viking missions, images of the Moon taken by the metric and the panoramic cameras from the Apollo missions, and images of Venus to be taken by synthetic aperture radar systems from the planned future Venus Radar Mapper mission. The following sections discuss image quality, measuring capability, and mapping methods and equipment separately for Mars, the Moon, and Venus.

1. MARS

Mariner 4 took man's first close-up pictures of the Martian surface. It photographically covered about 1% of the Martian surface at approximately three kilometer resolution. Mariner 6 and 7 then extended the Martian photographic coverage up to 10% and also improved man's viewing resolution to 0.3 kilometers (Leighton and Murray, 1971). But it was Mariner 9, that photographically covered almost the entire surface of Mars and gave us major new knowledge of Mars. During a period of 349 days in Martian orbit, it transmitted to Earth, more than 7,300 pictures of Mars.

Mariner 9 images, reconstructed from reduced data record tapes on an Optronics Photowrite device, provided stereo models for photogrammetric map compilations. Since most models could only be constructed by combining pictures taken from different orbits, unconventional photogrammetric procedures were developed on an analytical stereoplotter (Wu et.al., 1973). Contour maps of prominent Martian features were actually compiled stereoscopically on the analytical stereoplotter. Contour intervals of 1 km and 200 m were obtained respectively from the wide angle and narrow angle cameras which respectively had focal lengths of 52.267 mm and 500.636 mm. Their fields of view are respectively 11° x 14° and 1.1° x 1.4°. Applying analytical photogrammetric methods, using Mariner 9 images, a primary control net of Mars has been accomplished (Davies et.al., 1978). This control net has been adopted for providing horizontal controls for photo mosaic maps.

More than 60,000 pictures from the Viking missions have opened Mars to intensive investigation in many fields. Topographic maps are in high demand for scientific studies and for planning future Mars missions. Despite the fact that the Viking Orbiter pictures have extremely narrow fields of view, special techniques have been developed to allow stereo compilation (Wu et.al., 1982b). These techniques require computation of orientation parameters of the stereo models on the AP/C, the AS-11A, and the AS-11B-1 analytical stereoplotters. In order to adjust uncertainties of camera pointing angles (0.25°) and inconsistencies in SEDR (the Supplementary Experiment Data Record) for computing stereo-model parameters, a block adjustment was accomplished using more than 700 Viking Orbiter pictures of Mars (Wu and Schafer, 1984). This development makes it possible to use high-quality photographs from the Viking mission, of various ranges of resolution, to systematically map the planet Mars at various scales, 1:2,000,000, 1:1,000,000, 1:500,000 and larger.

The computation of model-orientation parameters is developed on the AP/C, AS-11A and AS-11B-1 analytical stereoplotters as described below (Wu et.al., 1982b).

Let ω_1, ϕ_1, κ_1, X_1^0, Y_1^0, Z_1^0 and ω_2, ϕ_2, κ_2, X_2^0, Y_2^0, Z_2^0 be orientation (roll, pitch, and yaw) and position parameters, respectively, for photographs 1 (left) and 2 (right). For vertical or near-vertical photographs, the point projected on the Martian surface from the midpoint of the camera base can serve as the model center; a local secant coordinate system can also be arbitrarily chosen at the point of tangency of the camera midpoint. However, for those photographs with high tilt angles, the center of gravity of the entire overlapped area in the model serves better for the point of tangency. Therefore, two different points of tangency can be chosen, depending on the tilt angle of the photographs. In the case of vertical or near-vertical photographs, the coordinates of the point of tangency are:

$$\begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} = \frac{R}{D'} \begin{pmatrix} X_0' \\ Y_0' \\ Z_0' \end{pmatrix} \tag{1}$$

where R is the radius of Mars at the tangent point; this radius can be obtained either from a table or by using the existing computer program of the Mars topographic datum (Wu, 1975, 1978). D' is a scalar that can be determined by:

$$D' = [X_0'^2 + Y_0'^2 + Z_0'^2]^{1/2} \tag{2}$$

X_0', Y_0', and Z_0' are the coordinates of the midpoint of the camera base and are determined by:

$$\begin{pmatrix} X_0' \\ Y_0' \\ Z_0' \end{pmatrix} = 1/2 \left[\begin{pmatrix} X_1^0 \\ Y_1^0 \\ Z_1^0 \end{pmatrix} + \begin{pmatrix} X_2^0 \\ Y_2^0 \\ Z_2^0 \end{pmatrix} \right] \tag{3}$$

Then, the geographic coordinates of the point of tangency are:

$$\lambda_0 = \tan^{-1}(Y_0/X_0) \tag{4}$$

$$\phi_0 = \tan^{-1}\left(\frac{a^2}{b^2}\tan\Psi_0\right) \tag{5}$$

where $\Psi_0 = \tan^{-1}(Z_0/\sqrt{(X_0^2 + Y_0^2)})$ and a and b are, respectively, the semi-major and semi-minor axes of Mars.

Let A_1 be the rotation matrix, which rotates from Martian coordinates to the local secant coordinates as:

$$A_1 = [\phi_0][\lambda_0] = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sin\phi_0 & \cos\phi_0 \\ 0 & -\cos\phi_0 & \sin\phi_0 \end{pmatrix} \begin{pmatrix} -\sin\lambda_0 & \cos\lambda_0 & 0 \\ -\cos\lambda_0 & -\sin\lambda_0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} -\sin\lambda_0 & \cos\lambda_0 & 0 \\ -\sin\phi_0\cos\lambda_0 & -\sin\phi_0\sin\lambda_0 & \cos\phi_0 \\ \cos\phi_0\cos\lambda_0 & \cos\phi_0\sin\lambda_0 & \sin\phi_0 \end{pmatrix} \tag{6}$$

Then, referring to the local secant coordinate system, with the Y axis pointing to the north, the position coordinates, X, Y, and Z, of each camera can be determined:

$$\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} = (A_1) \left[\begin{pmatrix} X_i^0 \\ Y_i^0 \\ Z_i^0 \end{pmatrix} - \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} \right] \tag{7}$$

where i = 1 and 2 refers to cameras 1 and 2. Let $\bar{\kappa}$ be the local rotation angle; then the rotation matrix, which refers to the local system, is:

$$A_2 = \begin{pmatrix} \cos\bar{\kappa} & \sin\bar{\kappa} & 0 \\ -\sin\bar{\kappa} & \cos\bar{\kappa} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{8}$$

where

$$\bar{\kappa} = \tan^{-1}[(Y_2 - Y_1)/(X_2 - X_1)] \tag{9}$$

In this local system the object-space components B_x, B_y, and B_z of each camera station are:

$$\begin{pmatrix} Bx_i' \\ By_i' \\ Bz_i' \end{pmatrix} = (A_2) \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} \tag{10}$$

Then the scaled-down parameters of each photograph position used to set up the model are:

$$\begin{pmatrix} Bx_i \\ By_i \\ Bz_i \end{pmatrix} = S \begin{pmatrix} Bx_i' \\ By_i' \\ Bz_i' \end{pmatrix} \tag{11}$$

where

$$S = f/[1/2(Bz_1' + Bz_2')] \tag{12}$$

and f is the focal length of the camera, or the principal distance of the photographs used in the model.

Let C be the rotation matrix that rotates from local to camera coordinates for each camera station:

$$[C_i] = (R_i)\ (A_1)^T\ (A_2)^T \tag{13}$$

where (R_i) is the photogrammetric rotation matrix formed by the sequential rotation matrices. These matrices are the primary ω matrix about the X axis, the secondary ϕ matrix about the Y axis, and the tertiary κ matrix about the Z axis:

$$(R_i) = [\kappa]\ [\phi]\ [\omega] \tag{14}$$

Then, the rotational parameters for each photograph in the model can be obtained by:

$$\begin{aligned} \bar{\omega}_i &= \sin^{-1}\ (C_{23}) \\ \bar{\phi}_i &= \tan^{-1}\ (-C_{13}/C_{33}) \\ \bar{\kappa}_i &= \tan^{-1}\ (-C_{12}/C_{22}) \end{aligned} \tag{15}$$

The stereomodel setup is accomplished by entering the computed model parameters as defined in equations (11) and (15) into the computer of the analytical stereoplotters. The immediate result is a stereo model that is equivalent to a stereo model obtained through the ordinary processing of relative orientation. Contour lines are then compiled.

Because the model orientation parameters are computed using the adjusted SEDR data in the control net adjustment, stereo models derived with these parameters are close to those derived from the absolute orientation parameters. The computation of absolute orientation does not change the model orientation parameters significantly except where map projections differ.

Software for this technique has been developed on the analytical stereoplotters. Adjusted camera positions and attitudes of the 714 Viking pictures have been stored into a moving head disc so that all the computations can be done in real-time processing. As soon as the plotter operator enters the identification of the pair of photographs of the model and performs the interior orientation, a stereo model is established immediately. In the situation where the operator decides to perform an absolute orientation of the model, all he has to do is to enter identification of control points desired to be used. The computer searches those control points from the master file in the disc and performs the absolute orientation immediately. About 3,000 control points of Mars established from the Mars planet-wide control network (Wu and Schafer, 1984) have also been stored on the disc in both geodetic and Cartesian coordinate systems. Using this technique, Mars maps at various scales have been and are being compiled. The smallest contour interval yet attempted with Viking Orbiter pictures is 20 meters.

Because of advances in computerized image processing techniques, with 103 reseau marks in the Viking picture, distortions of decalibrated pictures can be reduced to less than a pixel (Ruiz, 1976, Wu et.al., 1982b). At an altitude of 1500 km, the ground resolution is about 37.5 m. With a low-sun-angle picture, standard errors of repeatability in the elevation measurements are small, ranging from 12.7 m to 22.2 m. The maximum S.E. from photography of the same condition is 33.9 m.

Imagery from the facsimile cameras on the Viking Lander vehicle is composed of image elements recorded by scanning in both horizontal and vertical directions. This is virtually equivalent to images on a spherical surface. The solution to the problem of photogrammetric mapping using such close-range images is to convert the scanning imagery to the equivalent of a frame picture so that the present available analytical stereoplotters can be used for map compilation. The most accurate method is to make the image conversion and corrections in real time on an analytical stereoplotter (Wu and Schafer, 1982). Conversion equations are based on a gnomonic projection,

$$x = f \frac{\text{Sin}\ \Delta\lambda}{\text{Sin}\ E_0 \tan E_p + \text{Cos}\ E_0 \cos \Delta\lambda} \tag{16a}$$

$$y = f \frac{\text{Cos}\ E_0 \tan E_p - \sin E_0 \cos \Delta\lambda}{\sin E_0 \tan E_p + \cos E_0 \cos \Delta\lambda} \tag{16b}$$

Where $\Delta\lambda$ and E_p are azimuth and elevation elements of an image points and x and y are the corresponding converted image coordinates along the azimuth and elevation directions; E_0 is the elevation of the camera axis. Software has been developed on the AS-11A analytical stereoplotter. Map precision, aside from the effect of image rersolution, is primarily determined by the performance of the camera servo mechanisms. With appropriate geometric correction made to high-resolution images (0.04°), horizontal precision varies from 10 mm to 266 mm at points from the front center to the far corners of the mapped area which is about 5 m by 8 m in front of the two cameras with a fixed base of 0.821 m betwen the two cameras. Using low-resolution images (0.12°), map precision ranges from 19 mm to 400 mm (Wu et.al., 1982a).

2. THE EARTH MOON

As previously mentioned, a sophisticated photogrammetric system was installed on board each of the Apollo 15, 16, and 17 missions. Based on the known positions and orientations of camera stations provided by tracking data, orbital ephemerides, a selenocentric geodetic reference system has been established using Apollo metric photographs (Doyle et.al, 1977). For the mission planning and mission operation and other specialized scientific studies, numerous topographic maps of the Moon have been compiled at various scales 10,000, 1:50,000, 1:250,000 and 1:2,750,000 using photographs from the metric and panoramic cameras (Wu and Moore, 1980, Wu, 1984). Standard methods and procedures were applied for map compilation for most of the lunar images except those that were taken by the panoramic cameras. For compilation of panoramic photography, special software on the AS-11A and AS-11B-1 analytical stereoplotters was used. With analytical plotters a 0.64 m and 8.6 m precision of elevation measurements was obtained respectively from the panoramic and the metric photographs (Wu and Moore, 1980). Photographs of the panoramic camera and the metric camera have resolutions of respectively 180 and 200 lines/mm.

3. FUTURE DEVELOPMENT--VENUS RADAR MAPPER

For the Venus Radar Mapper (VRM) mission, the Photogrammetry Section of the Branch of Astrogeology, U. S. Geological Survey, at Flagstaff, AZ, has been continuing to conduct research and development in mapping, using side-looking radar images. Because of the unique radar geometry, mainly effected by its method of illumination and image formation, topographic contour maps cannot be directly compiled on conventional stero-photogrammetric equipment. Various approaches have been attempted and experiments have been performed (Wu, 1979, Wu et.al., 1980). One approach interfaces the existing radar steroplotter to a Modcomp computer so that ground coordinates can be determined by measuring radar image coordinates through stereoscopic viewing. Interface hardware is completed and software development is in progress. Since the studies of stereo radar-mapping problems emphasize geometric correction and have advanced to a point where the radar layover problem can be mathematically solved (Wu, 1983), the current approach is to modify the existing software used for map compilation from panoramic photography on the analytical stereoplotter, which also has a line-scan geometry. Once the layover distortion is corrected, the stereo model should be retained on the plotter. Stereo radar compilation will then be performed using practically the same procedures, i.e., interior, relative, and absolute orientations that are used in conventional photogrammetry. Future development of stero radar compilation will probably involve automatic image correlation.

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