# METHODS OF THE BUNDLE BLOCK ADJUSTMENT OF PLANETARY IMAGE DATA

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**KEY WORDS:** planetary image data, Sequent method, Robust, Baarda, variance estimation, bundle block adjustment

## ABSTRACT

We have developed procedures for bundle block adjustments of planetary images obtained by framing cameras. The "Sequent" method was developed for the elimination of a priori gross errors in the input image point coordinates during the preparation of the data. The "Robust" and the "Baarda" methods eliminate any further errors during the block adjustment. The procedure also identifies and eliminates systematic offsets and drift in navigation observations. Finally, variances of image coordinates, navigation parameters and object coordinates of control points are estimated. The procedure was verified using simulated data and finally applied to lunar Clementine image data of a region in the eastern Mare Orientale. The precision of the object coordinates was improved from a standard deviation of 2500 m before the adjustment, to 150 m after the adjustment.

## 1. INTRODUCTION

The bundle block adjustment plays a central role in the photogrammetric analysis of image data. The procedure allows us to correct nominal navigation parameters, and yields precise object coordinates of conjugate image points. Adjusted navigation data will typically be used in the production of DTMs (Digital Terrain Models), mosaic images, orthophoto images, and control point networks. In comparison with the classical aerial photogrammetric techniques, the bundle block adjustment of planetary images faces several challenges: navigation parameters are only known to a limited precision, and they can contain systematic errors, such as offset and drift. Furthermore, on planetary surfaces, normally very few control points are available. This paper expands on these specific problems and presents existing or develops new methods for their solution *).

Finally, the methods are applied to Clementine images that were obtained in two areas on the Moon near Mare Orientale. The adjusted results show that these methods are robust and reliable.

## 2. CHARACTERIZATION OF PLANETARY IMAGE DATA

The position parameters of a spacecraft, and the orientation parameters of a framing camera are inertially measured and are known to a certain precision. These quantities can be transformed into six navigation parameters (X, Y, Z, $\varphi$, $\omega$, $\kappa$) in the photogrammetric system which are introduced into the bundle block adjustment as uncorrelated observations. Images are typically obtained from several different orbits, or even from different cameras in different missions. Therefore, navigation parameters of single images can also have different precisions.

Typically, for most planetary surfaces, there are very few control points, and their precision is usually worse than the pixel resolution of the surface seen in the image. Even for the Moon there are less than 2000 control points (Davies et al., 1994).

## 3 . PREPARATION OF IMAGE DATA

First, large numbers of image coordinates of conjugate image points are measured manually on the computer screen. These are transformed into the photogrammetric system.

For the bundle block adjustment, initial values of object coordinates of these conjugate points are needed. These are calculated using the forward intersection method for each point. For the elimination of gross errors in the image measurements, a procedure has been developed, we will refer to as the "Sequent" method. Initially the best stereo image pair is specified. This pair must satisfy simultaneously three requirements, a long base, a small standard deviation of conjugate points, and a small standard deviation on the unit weight. If the standard deviation of the conjugate point, for all pairs, is larger than the given limit value, then this point is regarded as a "bad" point and is eliminated. If the best pair for this conjugate point is found, we continue the adjustment for this conjugate point. In every subsequent step, a new image point is introduced. If the standard deviation of this conjugate point is larger than the limit value, this new image point is designated as a "bad" image point, and is eliminated, thus removing all large errors. From this we obtain a reliable set of object coordinates for the future bundle block adjustment.

## 4 METHOD OF THE ADJUSTMENT

In the second stage of the process, the actual bundle block adjustment is performed. The navigation parameters and object coordinates are the unknowns. The image coordinates are from

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*) The methods described in this paper are implemented in the software package "DLRADJUST" which was written by the first author (W.Z.) and has been installed on computers at the DLR Institute of Planetary Exploration, Berlin-Adlershof.

one camera, or many cameras, the navigation parameters are from different orbits, and the object coordinates of control points are included as uncorrelated measurements in the adjustment. The navigation observations can be transformed through the spacecraft trajectory and the nominal camera orientation.
The offset and drift parameters of the navigation data can be used as observations in the adjustment, if their values are known. If we only know that offset and drift exist for the navigation, but we do not know their values, these parameters are used also as unknowns in the adjustment. We will discuss this problem further in section 4. 3.

The collinearity condition is the basis for the bundle block adjustment (Kraus, 1994). It consists of non-linear equations. After linearization of the collinearity equations, we obtain the following error equations:

$$\begin{aligned} v_{i(x)} &= a_{i(x)} x0_j + a_{i(y)} y0_j + a_{i(z)} z0_j \\ &+ a_{i(\varphi)} \varphi_j + a_{i(\omega)} \omega_j + a_{i(\kappa)} \kappa_j \\ &- a_{i(x)} x_k - a_{i(y)} y_k - a_{i(z)} z_k - l_{i(x)}, \end{aligned} \quad (1)a$$

$$\begin{aligned} v_{i(y)} &= b_{i(x)} x0_j + b_{i(y)} y0_j + b_{i(z)} z0_j \\ &+ b_{i(\varphi)} \varphi_j + b_{i(\omega)} \omega_j + b_{i(\kappa)} \kappa_j \\ &- b_{i(x)} x_k - b_{i(y)} y_k - b_{i(z)} z_k - l_{i(y)}. \end{aligned} \quad (1)b$$

These unknowns represent the six elements of the navigation ($x0_j$, $y0_j$, $z0_j$, $\varphi_j$, $\omega_j$, $\kappa_j$) for image j, and the object coordinates for the conjugate point k ($x_k$, $y_k$, $z_k$). $v_{i(x)}$ and $v_{i(y)}$ are the improvements for the image point i.

The error equations of the other observations are summarized as follows:

For the control point observations of point k:

$$v_{k(x)} = x_k - l_{k(x)}, \quad (2)a$$
$$v_{k(y)} = y_k - l_{k(y)}, \quad (2)b$$
$$v_{k(z)} = z_k - l_{k(z)}, \quad (2)c$$

where $l_{k(x)}$, $l_{k(y)}$ and $l_{k(z)}$ are the observations.

For the spacecraft position observations of image j:

$$v_{j(x0)} = x0_j - l_{j(x0)} - c_{n(x0)} - s_j d_{n(x0)}, \quad (3)a$$
$$v_{j(y0)} = y0_j - l_{j(y0)} - c_{n(y0)} - s_j d_{n(y0)}, \quad (3)b$$
$$v_{j(z0)} = z0_j - l_{j(z0)} - c_{n(z0)} - s_j d_{n(z0)}, \quad (3)c$$

where $l_{j(x0)}$, $l_{j(y0)}$ and $l_{j(z0)}$ are the observations.

For the spacecraft orientation observations of image j:

$$v_{j(\varphi)} = x_j - l_{j(\varphi)} - c_{n(\varphi)} - s_j d_{n(\varphi)}, \quad (4)a$$
$$v_{j(\omega)} = y_j - l_{j(\omega)} - c_{n(\omega)} - s_j d_{n(\omega)}, \quad (4)b$$
$$v_{j(\kappa)} = z_j - l_{j(\kappa)} - c_{n(\kappa)} - s_j d_{n(\kappa)}, \quad (4)c$$

where $l_{j(\varphi)}$, $l_{j(\omega)}$ and $l_{j(\kappa)}$ are the observations.

In (3) and (4), $c_{n(\cdot)}$ and $d_{n(\cdot)}$ are the offset and drift of the navigation parameters for orbit (group) n. $s_j$ is the distance difference of the orbit for image j.

The unknowns, their standard deviations, and the corrections of the observations are calculated using the method of least squares with reference to these error equations.

### 4. 1 The Robust and Baarda method

We can use the Robust method (Klein et al. 1984) and the Baarda method (Baarda, 1968) for the elimination of gross errors of the observations in the bundle block adjustment. The Robust (Danish method) can identify quickly a large number of blunders in a single run, but the method is less effective if the redundancy numbers show great variation. The Robust method eliminates only gross errors in image observations, but does not search for gross errors in other observations (position, orientation, and control points). The results (Table 2) show that if very large errors exist in the observations this method will not find all of them.

The Baarda method is much better at finding gross errors in all observations. We can search for gross errors not only in image observations, but also in position, orientation, and control point observations using this method. There are generally no, or very few control points available for the adjustment of planetary image data. Therefore the navigation parameters for every image, should also be used as observations in the adjustment. An observation, which contains a gross error, is not always eliminated, but instead a smaller weight is applied to the measurement. For example, $P_{new} = P_{old} / 5$, where $P_{old}$ is the correct weight. The new weight $P_{new}$ is then used for this "bad" navigation observation, in further iterative adjustments.

The Baarda method is allowed to eliminate only the largest error in every iterative adjustment. Unfortunately this method requires more computing time if there are a large numbers of gross errors.

### 4. 2 Variance estimation

There are a lot of different kinds of observations in the adjustment of planetary image data. Every kind of observation has a specific precision, but these are unfortunately unknown.

A priori variance of the observations need not be known, if there is only one kind of observation for the adjustment. But a priori variances must be used for determining the weights in the adjustment with more than one kind of observation. We can use the mathematical method of variances estimation (Roa 1971). Zhang (1990, 1994) has successfully used this method in the adjustment of a network with angle and distance measurements, and in the adjustment of gravity measurements.

This method is used in the paper for the bundle block adjustment of planetary image data. The observations apply to single groups. The image observations divide into "n" groups, if the images are taken from "n" cameras, The position and orientation observations are created in "m" groups, if the navigation parameters belong to "m" orbits. The object coordinates of control points belong to another group. The a priori variances of all observation groups are calculated during the bundle block adjustment. The estimated values of the a prirori variances are used in the last step of the adjustment.

### 4. 3 Method for elimination of systematic errors in the navigation observations

Planetary image data are obtained normally from many orbits. The corresponding time difference can be very large. From this, the navigation parameters between different orbits, and every navigation parameter within a orbit, can contain variable offsets and drifts. We define one offset and one drift for every navigation parameter within an orbit.

Because the initial navigation data are not well known, and difficult to estimate, we will adjust only those parameters which have the most influence on the results of the adjustment. The least influential navigation data remain fixed.

For the elimination of the systematic errors, we perform the bundle block adjustment in several stages:
In the first adjustment, we assume that there is no offset and drift. After this adjustment we have improved the navigation observations. Using the method of least squares reference to the following equations, we can calculate the offsets (eq. (5)), or the offsets and drifts (eq. (6) ):

$$v_{j(\cdot)} = c_{n(\cdot)} , \qquad (5)$$

or

$$v_{j(\cdot)} = c_{n(\cdot)} - s_j d_{n(\cdot)} , \qquad (6)$$

where $"\cdot" = x0, y0, z0, \varphi, \omega, \kappa$ .

The meaning of the other symbols was explained earlier.

The adjusted offsets and drifts for all groups of the navigation data and the standard deviations are stored in an output file. With the output information, we can determine which navigation data contain the systematic errors. If the adjusted offset and drift in (6) are larger than their standard deviations, this implies that the navigation data contains systematic errors. If this requirement is satisfied only for an offset (eq. (5) ), there exists only an offset parameter. Because the adjusted parameters are correlated, the estimated values are probably not correct. We can only detect whether there exist offsets and drifts in the navigation data, by this approximate method.

In the second adjustment, the offsets and drifts found are used as unknowns in the bundle block adjustment (eq. (3) and (4) ). The offsets and drifts, to which the estimated values are much larger than their standard deviations in this adjustment, are used as unknowns in the last adjustment.

## 5. SIMULATED CALCULATION

In our bundle block adjustment of planetary image data, simulated and practical tests were carried out. The simulated data are useful for checking the correctness of our methods. The simulated data are produced as follows: First, we carry out the bundle block adjustment for the example image data (a part of Test 1 in the section 6) resulting in adjusted object coordinates. In the second step, we use the backward method for the calculation of the image coordinates for these object points. Finally, we add known random errors, known gross errors, and known systematic errors (offset and drift) into the observations. The simulated data come from two cameras, and two orbits (Table 1).

| Control points | Number of images | Conjugate points | Image points | Size of pixel |
|---|---|---|---|---|
| 10 | 32 | 40 | 344 | 150 (m) |

Table 1: Simulated data

### 5. 1 Elimination of gross errors

Thous, our simulated data contain twenty gross errors in the image observations, one gross error in the position, in the orientation and in the control point observations. Ten of the gross errors in the image coordinates are "large errors". Their values lie between 500 and 3000 (pixels) (group 1), that is, the actual values are very much larger than their true values. There are ten gross errors in the image coordinates (group 2).

The three methods, Sequent, Robust and Baarda, are applied separately here for searching for gross errors. All ten "large errors" in the image coordinates are eliminated by the Sequent method, in the first step of the adjustment. The Robust method finds only seven "large errors" in the image coordinates. The remaining errors, particularly the three "large errors", greatly corrupt the adjusted results. In comparison, the Baarda method finds all gross errors, in all observations (Table 2).

| Error types | Size of errors | Sequent | Robust | Baarda |
|---|---|---|---|---|
| group 1 of image points | 500 (pix.) to 3000 | 10 / 10 | 10 / 7 | 10 / 10 |
| group 2 of image points | 10 (pix.) to 40 | 10 / 0 | 10 / 0 | 10 / 10 |
| positions | 2 (km) | - | - | 1/ 1 |
| orientations | 0.2 (deg) | - | - | 1 / 1 |
| control points | 2 (km) | - | - | 1 / 1 |
| limit value = 10 (km) for the Sequent method<br>limit value = 4 for the Baarda method | | | | |

Table 2: Elimination of gross errors I

| Error types | Sequent Robust | Sequent Baarda |
|---|---|---|
| group 1<br>group 2 | 10 / 10<br>10 / 9 | 10 / 10<br>10 / 10 |
| positions<br>orientations<br>points | -<br>-<br>- | 1 / 1<br>1 / 1<br>1 / 1 |

Table 3: Elimination of gross errors II

In practice we always use the Sequent method during the first step of the adjustment. After that, the Robust, or the Baarda method are used in the bundle block adjustment. In this example, the Sequent method has eliminated the ten "large errors" in the image measurements; the Robust method finds nine errors in these observations. The Baarda method has found ten errors in the image measurements and all three gross errors in the other observations (Table 3). These results show, we should either use, in combination, the Sequent and the Baarda method, or the Sequent and the Robust method, in the bundle block adjustment.

### 5. 2 Variance estimation

The simulated data contain five kinds of observation: two groups of image coordinates (two cameras), two groups of position orientation observations, and one group of object coordinates of the control points. We can simultaneously estimate five a priori variances of the observations during the adjustment. Only the priori variances of the image coordintes are estimated, or the a priori variances of image coordinates and the position observations are calculated. We have given all modules, with different values of variances. The results of two examples are listed in Table 4 (example I) and Table 5 (example II). Three different initial values are used in each test (initial 1, initial 2, and initial 3). All results show that the estimated a priori variances are identical with their true values, and they are not dependent upon their initial values (Table 4 and Table 5).

| Values | Image points (mm) | Position data (m) | Orientation data (deg) | Control points (m) |
|---|---|---|---|---|
| true | 0.02<br>0.005 | 100<br>500 | 0.01<br>0.05 | 200 |
| initial 1 | 1.0<br>1.0 | 200<br>1500 | 0.01<br>0.15 | 600 |
| estimated 1 | 0.0196<br>0.0051 | 99.4<br>450.8 | 0.095<br>0.055 | 196.5 |
| initial 2 | 0.01<br>0.01 | 200<br>1500 | 0.01<br>0.15 | 600 |
| estimated 2 | 0.0196<br>0.0051 | 88.8<br>454.6 | 0.011<br>0.054 | 195.9 |
| initial 3 | 0.0001<br>0.0001 | 200<br>1500 | 0.01<br>0.15 | 600 |
| estimated 3 | 0.0196<br>0.0051 | 88.8<br>454.6 | 0.011<br>0.056 | 195.9 |

Table 4: A priori variances for the example I

| Values | Image points (mm) | Position data (m) | Orientation data (deg) | Control points (m) |
|---|---|---|---|---|
| true | 0.1<br>0.1 | 2000<br>2000 | 0.2<br>0.2 | 1000 |
| initial 1 | 1.0<br>1.0 | 10000<br>10000 | 1.0<br>1.0 | 5000 |
| estimated 1 | 0.095<br>0.101 | 2204.8<br>1826.3 | 0.235<br>0.23 | 958.9 |
| initial 2 | 0.01<br>0.01 | 10000<br>10000 | 1.0<br>1.0 | 5000 |
| estimated 2 | 0.095<br>0.101 | 2187.8<br>1888.1 | 0.238<br>0.228 | 998.9 |
| initial 3 | 0.0001<br>0.0001 | 10000<br>10000 | 1.0<br>1.0 | 5000 |
| estimated 3 | 0.095<br>0.101 | 2167.0<br>1918.3 | 0.236<br>0.235 | 991.1 |

Table 5: A priori variances for the example II

### 5. 3 Elimination of systematic errors

The simulated navigation data contain three offset parameters (example 1), or three offset and three drift parameters (example 2). Using our methods described in section 4.3, we have determined the systematic errors in the adjustment. All results show that the estimated offsets and drifts are in good agreement with their true values (Tables 6 and 7)

| | $c_{1(x0)}$ (m) | $c_{2(y0)}$ (m) | $c_{1(\kappa)}$ (deg) | Number of errors in other nav. |
|---|---|---|---|---|
| true values | 4000 | 2000 | 0.5 | - |
| times 1 | 2457<br>+/-560*) | 239<br>+/-89 | 0.21<br>+/-0.07 | 3 **) |
| times 2 | 4047<br>+/-29 | 1739<br>+/-271 | 0.59<br>+/-0.04 | 0 |
| results | 4047<br>+/-30 | 1632<br>+/-256 | 0.59<br>+/-0.04 | 0 |

Table 6: Elimination of systematic errors for example 1
*) standard deviation.
**): "3" means that besides the offsets $c_{1(x0)}$, $c_{2(y0)}$ and $c_{1(\kappa)}$, three offsets in the other navigation data are used as unknowns in the second adjustment.

| | $c_{1(x0)}$ $d_{1(x0)}$ (m, /km) | $c_{2(y0)}$ $d_{2(y0)}$ (m, /km) | $c_{1(\kappa)}$ $d_{1(\kappa)}$ (deg, /km) | Number of errors in other nav. |
|---|---|---|---|---|
| true values | 2000<br>2 | 1000<br>5 | 1.0<br>0.01 | - |
| times 1 | 705<br>+/-329<br>1.71<br>+/-1.35 | 557<br>+/-246<br>3.42<br>+/-0.79 | 1.16<br>+/-0.05<br>0.0208<br>+/-0.0002 | 4 |
| times 2 | 908<br>+/-300<br>4.25<br>+/-1.60 | 1500<br>+/-708<br>4.12<br>+/-2.41 | 1.22<br>+/-0.09<br>0.0197<br>+/-0.0003 | 0 |
| results | 2058<br>+/-64<br>1.95<br>+/-0.24 | 646<br>+/-354<br>4.94<br>+/-0.97 | 1.09<br>+/-0.07<br>0.0200<br>+/-0.0000 | 0 |

Table 7: Elimination of systematic errors for example 2

## 6 . RESULTS FOR CLEMENTINE IMAGE DATA

In 1994 approximately 600 000 images of the Moon were obtained from the UVVIS CCD-camera onboard the Clementine Mission (Table 8).

Stereo image sequences were taken in two areas near Mare Orientale. In this particular study area the ground pixel sizes of the images varied from 125 to 250 m. We have derived from these a local control point network, and two Digital Terrain Models (Oberst et al., 1996). We consider only the bundle block adjustment for the two areas, and analyse the results. The image data for the first area (Test 1) are taken from orbit 332. The

| | Clementine UVVIS |
|---|---|
| CCD chip size | 384 x 288 |
| focal length (mm) | 90.000 |
| pixel scale (pix/mm) | 43.478 |

Table 8: Clementine UVVIS camera

camera was slowly tilted within the orbit plane. The stereo images for the second area (Test 2) were selected from a combination of nadir images (orbit 333), and tilted images (orbits 334 and 338). The time difference between images taken on adjacent orbits is about five hours. The time difference between orbit 333 and orbit 338 is about 25 hours. Image data information is listed in Table 9.

| | Control points | Number of images | Conjugate points | Image points |
|---|---|---|---|---|
| Test 1 | 0 | 171 | 50 | 1785 |
| Test 2 | 6 | 96 | 417 | 1403 |

Table 9: Image data

The results in Test 2 show that offset and drift of the navigation data exist for orbit 388 (Table 10). Because the systematic errors are very large, we have used these adjusted parameters (the offset=4392 m, the drift= 2.004 m/km ) as observations in the further bundle block adjustment.

| | $c_{3(z0)}$ (m) | $a_{3(z0)}$ (m/km) |
|---|---|---|
| times 1 | 3620<br>+/-107 | 1.977<br>+/-0.266 |
| results | 4392<br>+/-61 | 2.004<br>+/-0.155 |

Table 10: Systematic errors for orbit 338 in Test 2 in the Z direction

The Sequent method is used for searching for gross errors in the Clementine data during the first step of the adjustment, the Robust, or the Baarda method, is used in the second step. The gross errors found in the observations, are given in Table 11. Two gross errors in the position observations, and one gross error in the orientation observations were found in Test 1 using the Baarda method. We did not eliminate the "bad" navigation observations, but low weights for these are applied (see section 4. 1).

The bundle block adjustment fails if the initial values of the object coordinates involve very large gross errors, and are not eliminated by the Sequent method in the adjustment.

| | Test 1 | | Test 2 | |
|---|---|---|---|---|
| | Conjugate points | Image points | Conjugate points | Image points |
| Sequent (20 km) | 3 | 29 | 31 | 35 |
| Robust | 0 | 21 | 1 | 7 |
| Baarda (5) | 0 | 35 | 1 | 5 |

Table 11: Elimination of errors for the Clementine data

The Clementine image data have three observation groups for Test 1: image coordinates, position and orientation observations. In comparison, the image data for Test 2 have three orbits and control points. Hence they have altogether eight groups of observations i.e., eight a priori variances are estimated in the adjustment. The a priori variances are presented in the Table 12.

The precisions of the navigation unknowns, and the precisions of the object coordinate unknowns are listed in Table 13. We also list the precisions of initial object coordinates in the first step and the object coordinates in the bundle block adjustment. The precisions of the object coordinates after the adjustment are essentially improved.

| | Test 1 | | Test 2 | |
|---|---|---|---|---|
| | initial values | estimated values | initial values | estimated values |
| image coordinates | (mm)<br>0.01 | 0.015 | 0.01 | 0.015 |
| control points | - | - | 150 | 48 |
| position for orbit 332 | (m)<br>200 | 430 | - | - |
| 333 | - | - | 400 | 141 |
| 334 | - | - | 400 | 195 |
| 338 | - | - | 400 | 134 |
| orientation for orbit 332 | (deg)<br>0.02 | 0.043 | - | - |
| 333 | - | - | 0.04 | 0.020 |
| 334 | - | - | 0.04 | 0.040 |
| 338 | - | - | 0.04 | 0.014 |

Table 12: A priori variances for the Clementine data

| | | Test 1 | Test 2 |
|---|---|---|---|
| mean precisions for adjusted positions | x | (m)<br>207 | 100 |
| | y | 379 | 134 |
| | z | 309 | 108 |
| mean precisions for adjusted orientations | $\varphi$ | (deg)<br>0.036 | 0.017 |
| | $\omega$ | 0.031 | 0.013 |
| | $\kappa$ | 0.041 | 0.019 |
| mean precisions for initial object coordinates | x | (m)<br>230 | 2044 |
| | y | 1103 | 2702 |
| | z | 547 | 987 |
| mean precisions for adjusted object coordinates | x | (m)<br>45 | 96 |
| | y | 130 | 150 |
| | z | 80 | 85 |

Table 13: Adjusted results for the Clementine data

Using the adjusted navigation parameters and the large number of image coordinates, which are found from the matching process, the object coordinates are calculated for all conjugate points. The Sequent method is used again for eliminating gross errors. Two digital Terrain Models have been produced using these adjusted object coordinates (Oberst et al. 1996).

The adjusted navigation parameters can also be used in the production of accurate mosaic images and orthophoto images. To demonstrate this, we produced two mosaic images using original navigation parameters (Fig. 1). adjusted navigation parameters (Fig. 2). The result is a clear improvement in the quality of the mosaic.

Fig. 1 : Mosaic image produced using nominal navigation data

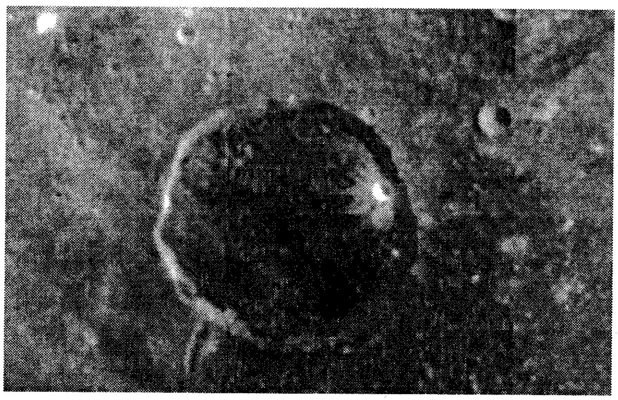

Fig. 2 : Mosaic image produced using adjusted navigation data

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