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Relative and Absolute Orientation Error Analysis

Unique and different conditions of extraterrestrial stereo mapping methods require complete and reliable results.

(*Abstract on page 1189*)

Introduction

The general solution of a photogrammetric stereopair consists of two steps; namely, relative and absolute orientation. However, in extraterrestrial cases their solution may become very difficult.

Relative Orientation

Relative orientation accuracy is influenced by these unfavorable conditions:

(1) TV transmission techniques result in low resolution pictures.
(2) Small vidicon format (approximately 12.5×12.5 mm.) allows only a very small base-to-height ratio.
(3) Vidicon reseau marks cannot achieve the accuracy of conventional fiducial marks.
(4) Lens distortion and atmospheric refraction usually are not known with sufficient accuracy.

The question now arises as to the accuracy of the final adjusted model coordinates. For terrestrial mapping purposes this is relatively unimportant because model coordinates are always transformed into a ground system, and the available ground control points supply sufficient and reliable accuracy criteria. For this reason, little attention has been given to these problems thus far. However, in extraterrestrial cases this is of utmost importance because of the absence of any ground control.

Absolute Orientation

After the relative orientation is achieved, the entire model must be translated, rotated, and scaled until it fits the required ground system. This transformation, of course, is an additional source of error which influences the ac-

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curacy of the final result. For extraterrestrial mapping purposes, where no ground control points are available, it is especially important to determine and analyze this influence, as this is the only way an accuracy estimate can be obtained.

RELATIVE ORIENTATION ERROR ANALYSIS

Although several approaches to the solution of the relative orientation problem exist, the approach based on the principle of collinearity has been chosen here because it seems to offer the most convenient way of solving the many required differentiations.

The entire concept of this procedure is shown schematically in Figure 1. The left camera system remains fixed; only the right system is rotated (ω'', ϕ'', k'') and translated (Y_0'', Z_0'') until all corresponding rays intersect at a proper elevation and without any model y-parallaxes. The x-component of the base X_0'' is deliberately chosen as equal to 1, because in relative orientation scaling is of no interest. This leaves five unknowns to be determined.

The following symbols were used:

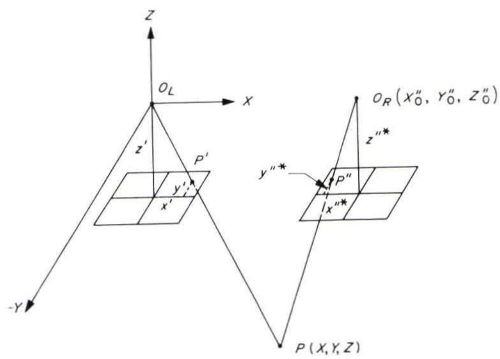

FIG. 1. Relative orientation of a stereopair based on the principle of collinearity.

X_0'', Y_0'', Z_0''	base components in the left camera system
x', y', x'', y''	observed image coordinates
z', z''	focal distances of the left and right cameras
x''^*, y''^*	image coordinates of the right plate rotated into a system parallel with the model system
z''^*	focal distance of the right camera rotated into the same system
A	three-dimensional orthogonal rotational matrix going from *ground* into *photo*
X, Y, Z	model coordinates of an observed point.

If the right camera is properly oriented (i.e., rotated and translated with respect to the left camera), model coordinates of any measured point can be computed:

$$Z = \frac{Z_0'' x''^* - z''^*}{x''^* - \frac{x'}{z'} z''^*} \tag{1}$$

$$X = \frac{x'}{z'} Z \tag{2}$$

$$Y = \frac{y'}{z'} Z. \tag{3}$$

However, the three rotational and two translational elements must first be determined. This is done by an iterative least squares method adjustment that has been described in many publications already and is widely known and used in analytical photogrammetry.

For the purpose of the following error analysis, Relations 1–3 can be conveniently rewritten as

$$Z = \frac{u_1}{u_2} \tag{1a}$$

$$X = u_3 Z \tag{2a}$$

$$Y = u_4 Z. \tag{3a}$$

These equations now enable a relatively simple differentiation:

$$dZ = d\frac{u_1}{u_2} = \frac{1}{u_2}(du_1 - Z\,du_2) \tag{4}$$

or, after substitution for du_1 and du_2 (all unmarked parameters pertain to the right camera system),

$$dZ = \frac{1}{u_2}\left[x^* dZ_O - (Z - Z_O)dx^* + (X - 1)dz^* + \frac{z^*}{z'} Z dx' - \frac{z^*}{z'} dz'\right] \tag{4a}$$

However, as

$$\begin{bmatrix} x^* \\ y^* \\ z^* \end{bmatrix} = \boldsymbol{A}^T \begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} = \boldsymbol{A}^T \boldsymbol{C}$$

Equation 4a can be further adapted to

$$dZ = \frac{1}{u_2}\left[T_1 d\omega + T_2 d\phi + T_3 dk + T_4 dZ_O + T_5 dx' + T_6 dz' + T_7 dx'' + T_8 dy'' + T_9 dz''\right] \tag{5}$$

where

$$T_1 = \begin{vmatrix} (X-1) & (Z-Z_0) \\ \dfrac{\partial A_1^T}{\partial \omega} C & \dfrac{\partial A_3^T}{\partial \omega} C \end{vmatrix}$$

$$T_2 = \begin{vmatrix} (X-1) & (Z-Z_0) \\ \dfrac{\partial A_1^T}{\partial \phi} C & \dfrac{\partial A_3^T}{\partial \phi} C \end{vmatrix}$$

$$T_3 = \begin{vmatrix} (X-1) & (Z-Z_0) \\ \dfrac{\partial A_1^T}{\partial k} C & \dfrac{\partial A_3^T}{\partial k} C \end{vmatrix}$$

$$T_4 = x^* = A_1^T C$$

$$T_5 = \frac{z^*}{z'} Z$$

$$T_6 = -\frac{z^*}{z'} X$$

$$T_7 = \begin{vmatrix} (X-1) & (Z-Z_0) \\ a_{11}^T & a_{31}^T \end{vmatrix}$$

$$T_8 = \begin{vmatrix} (X-1) & (Z-Z_0) \\ a_{12}^T & a_{32}^T \end{vmatrix}$$

$$T_9 = \begin{vmatrix} (X-1) & (Z-Z_0) \\ a_{13}^T & a_{33}^T \end{vmatrix}$$

Formula 5 could be considered as sufficient for most cases; however, to complete the analysis, one more influence must be anticipated; namely, the uncertainty of the principal point position with respect to the image center defined by fiducial marks.

It is evident from Figure 2 that real image coordinates must be written as

$$x = x_m - x_p \tag{6}$$

$$y = y_m - y_p \tag{7}$$

where x_m, y_m are the measured (observed) image coordinates and x_p, y_p are displacements of the principal point P with respect to the image center H.

Relations 6 and 7 can be simply differentiated and, after substitution into Equation 5, the final formula is obtained:

$$\begin{aligned} dZ = {} & S_1 d\omega + S_2 d\phi + S_3 dk + S_4 dZ_O + S_5 dx_m' \\ & - S_5 dx'_p + 0 dy_m' + 0 dy_p' + S_6 dz' + S_7 dx_m'' \\ & - S_7 dx_p'' + S_8 dy_m'' - S_8 dy_p'' + S_9 dz'' \end{aligned} \tag{8}$$

where

$$S_i = \frac{1}{u_2} T_i \qquad \text{for } i = 1, 2, \cdots, 9.$$

ABSTRACT: *Because of peculiarities of extraterrestrial photography (TV transmission, low resolution, small vidicon format, small base-to-height ratio etc.), relative orientation of a photogrammetric stereopair either cannot be reconstructed at all, or resulting residual and standard errors are excessively large. Therefore, instead of using observed image coordinates, exterior orientation data are used for a "forced" relative orientation. This way model coordinates can always be computed; however, the question of their accuracy is a critical one. Based on the principle of collinearity, the law of propagation of errors is applied to the basic analytical relative orientation relation, and a complete error analysis considering the influence of all involved parameters is derived. Absolute orientation represents then a similar problem, because in extraterrestrial cases ground control points usually are not available and therefore exterior orientation data must also be used. Again, a similar error analysis is determined. The relations were programmed for an IBM computer and, using different combinations of parameters, interesting statistical data were obtained.*

Following the same thought and differentiating Equations 2a and 3a, the following relations can be obtained for dX and dY:

$$\begin{aligned} dX = {} & u_3 S_1 d\omega + u_3 S_2 d\phi + u_3 S_3 dk + u_3 S_4 dZ_0 + (u_3 S_5 + S_{10}) dx_m' \\ & - (u_3 S_5 + S_{10}) dx_p' + 0 dy_m' + 0 dy'_p + u_3 (S_6 - S_{10}) dz' \\ & + u_3 S_7 dx_m'' - u_3 S_7 dx_p'' + u_3 S_8 dy_m'' - u_3 S_8 dy_p'' + u_3 S_9 dz'' \end{aligned} \tag{9}$$

$$\begin{aligned} dY = {} & u_4 S_1 d\omega + u_4 S_2 d\phi + u_4 S_3 dk + u_4 S_4 dZ_0 + u_4 S_5 dx_m' - u_4 S_5 dx_p' \\ & + S_{10} dy_m' - S_{10} dy_p' + u_4 (S_6 - S_{10}) dz' + u_4 S_7 dx_m'' - u_4 S_7 dx_p'' \\ & + u_4 S_8 dy_m'' - u_4 S_8 dy_p'' + u_4 S_9 dz'' \end{aligned} \tag{10}$$

where

$$S_{10} = \frac{Z}{z'} \cdot$$

Equations 8–10 can be rewritten in a compact matrix form

$$dX = S_X D \tag{9a}$$

$$dY = S_Y D \tag{10a}$$

$$dZ = S_Z D \tag{8a}$$

and the standard errors can be computed from

$$\begin{bmatrix} m_X{}^2 & m_{XY} & m_{XY} \\ m_{XY} & m_Y{}^2 & m_{YZ} \\ m_{XY} & m_{XY} & m_Z{}^2 \end{bmatrix} = \mu^2 \boldsymbol{S}\boldsymbol{Q}^2\boldsymbol{S}^T = \boldsymbol{M}^2$$

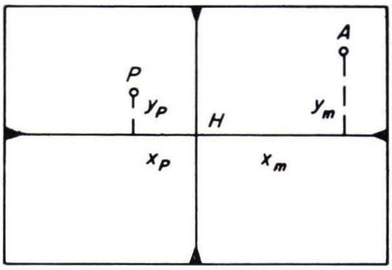

FIG. 2. Displacement of the principal point with respect to the image center. P, principal point; H, image center; A, observed point.

where μ is the standard error of unit weight, Q is the variance-covariance matrix of the 14 parameters, and

$$\boldsymbol{S}^T = (\boldsymbol{S}_X{}^T \boldsymbol{S}_Y{}^T \boldsymbol{S}_Z{}^T).$$

The preceding derivations were based on the assumption that the cameras were different; however, if the same camera is used tor both exposures, certain simplifications are possible. Namely, it is evident that

$$z' = z'' = z, \qquad x_p{}' = x_p{}'' = x_p, \qquad y_p{}' = y_p{}'' = y_p$$

and, after differentiation and substitution into Equations 8, 9, and 10, the following relations are derived:

$$\begin{aligned} dZ &= S_1 d\omega + S_2 d\phi + S_3 dk + S_4 dZ_0 + S_5 dx_m{}' + 0 dy_m{}' \\ &\quad + S_7 dx_m{}'' + S_8 dy_m{}'' - (S_5 + S_7) dx_p - S_8 dy_p + (S_6 + S_9) dz \end{aligned} \tag{12}$$

$$\begin{aligned} dX &= u_3 S_1 d\omega + u_3 S_2 d\phi + u_3 S_3 dk + u_3 S_4 dZ_0 + (u_3 S_5 + S_{10}) dx_m{}' \\ &\quad + 0 dy_m{}' + u_3 S_7 dx_m{}'' + u_3 S_8 dy_m{}'' - [u_3(S_5 + S_7) + S_{10}] dx_p \\ &\quad - u_3 S_8 dy_p + u_3(S_6 + S_9 - S_{10}) dz \end{aligned} \tag{13}$$

$$\begin{aligned} dY &= u_4 S_1 d\omega + u_4 S_2 d\phi + u_4 S_3 dk + u_4 S_4 dZ_0 + u_4 S_5 dx_m{}' \\ &\quad + S_{10} dy_m{}' + u_4 dx_m{}'' + u_4 S_8 dy_m{}'' - u^4(S_5 + S_7) dx_p \\ &\quad - (u_4 S_8 + S_{10}) dy_p + u_4(S_6 + S_9 - S_{10}) dz. \end{aligned} \tag{14}$$

Similarly, as before, one can write

$$d_X = \boldsymbol{R}_X \boldsymbol{D}_{red} \tag{13a}$$

$$d_Y = \boldsymbol{R}_Y \boldsymbol{D}_{red} \tag{14a}$$

$$d_Z = \boldsymbol{R}_Z \boldsymbol{D}_{red} \tag{12a}$$

and also

$$\boldsymbol{M}^2 = \mu^2 \boldsymbol{R} \boldsymbol{Q}^2{}_{red} \boldsymbol{R}^T \tag{15}$$

where Q_{red} is the reduced variance-covariance matrix of 11 parameters only, and

$$\boldsymbol{R}^T = (\boldsymbol{R}_X{}^T \boldsymbol{R}_Y{}^T \boldsymbol{R}_Z{}^T).$$

ABSOLUTE ORIENTATION ERROR ANALYSIS

In conventional analytical absolute orientation, known ground control points are first transformed into the model system and then all model coordinates are transformed back into the ground system. Statistical data obtained by this least-squares method of adjustment give us then sufficient accuracy criteria.

However, in most extraterrestrial cases no ground control points are available and instead of an adjustment *external* orientation data are used. The necessity of a reliable error analysis is then evident.

The transformation can be written in a compact matrix form:

$$\boldsymbol{X} = s\boldsymbol{A}^T \mathrm{x} + \boldsymbol{B} \tag{16}$$

where

$$\boldsymbol{X} = \begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix}, \quad \mathrm{x} = \begin{bmatrix} X_M \\ Y_M \\ Z_M \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} b_X \\ b_Y \\ b_Z \end{bmatrix}$$

s = scale factor

A^T = rotational matrix going from *model* into *ground.*

Therefore, there are ten parameters involved in the error analysis: three rotations (ω. ϕ, k), one scale factor (s), three translations (b_X, b_Y, b_Z), and three model coordinates (X_M, Y_M, Z_M).

The necessary differentiation of Formula 16 is relatively easy:

$$\begin{aligned} dX &= s\frac{\partial A^T}{\partial\omega} x d\omega + s\frac{\partial A^T}{\partial\phi} x d\phi + s\frac{\partial A^T}{\partial k} x dk + A^T x ds \\ &+ \frac{\partial B}{\partial b_x} db_X + \frac{\partial B}{\partial b_y} db_Y + \frac{\partial B}{\partial b_z} db_Z + sA^T \frac{\partial x}{\partial X_M} dX_M \\ &+ sA^T \frac{\partial x}{\partial Y_M} dY_M + sA^T \frac{\partial x}{\partial Z_M} dZ_M \end{aligned} \tag{17}$$

or, in a simplified matrix form,

$$d\boldsymbol{X} = \boldsymbol{P}\boldsymbol{U} \tag{17a}$$

where

$$d\boldsymbol{X} = \begin{bmatrix} dX_G \\ dY_G \\ dZ_G \end{bmatrix}, \qquad \boldsymbol{P} = (\boldsymbol{P}_1 \boldsymbol{P}_2 \cdots \boldsymbol{P}_{10})$$

$$\boldsymbol{U}^T = (d\omega\, d\phi\, dk\, ds\, db_X\, db_Y\, db_Z\, dX_M\, dY_M\, dZ_M)$$

and also

$$\boldsymbol{P}_1 = s\begin{bmatrix} 0 & 0 & 0 \\ -a_{13} & -a_{23} & -a_{33} \\ a_{12} & a_{22} & a_{32} \end{bmatrix} \mathrm{x}$$

$$\boldsymbol{P}_2 = s\begin{bmatrix} (-\sin\phi\cos k) & (\sin\phi\sin k) & (\cos\phi) \\ (\sin\omega\cos\phi\cos k) & (-\sin\omega\cos\phi\sin k) & (\sin\omega\sin\phi) \\ (-\cos\omega\cos\phi\cos k) & (\cos\omega\cos\phi\sin k) & (-\cos\omega\sin\phi) \end{bmatrix} \mathrm{x}$$

$$P_3 = s\begin{bmatrix} a_{21} & -a_{11} & 0 \\ a_{22} & -a_{12} & 0 \\ a_{23} & -a_{13} & 0 \end{bmatrix} x \qquad P_4 = A^T x$$

$$P_5 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \qquad P_6 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \qquad P_7 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$P_8 = s\begin{bmatrix} a_{11} \\ a_{12} \\ a^{13} \end{bmatrix} \qquad P_9 = s\begin{bmatrix} a_{21} \\ a_{22} \\ a_{23} \end{bmatrix} \qquad P_{10} = s\begin{bmatrix} a_{31} \\ a_{32} \\ a_{33} \end{bmatrix}.$$

Finally, as in the case of relative orientation, standard errors can be computed:

$$m_X{}^2 = PQ_2P^T\mu^2 \tag{18}$$

where μ is the standard error of unit weight and Q is the variance-covariance matrix of the ten parameters involved.

Statistical Results

To prove the correctness of the theoretical analysis described above, and to obtain a reliable conception of the practical applicability of extraterrestrial mapping techniques, four hypothetical stereo models were constructed:

(1) Image format 20×20 cm, focal distance $=100$ mm.
(2) Vidicon format, focal distance $=25$ mm.
(3) Vidicon format, focal distance $=50$ mm.
(4) Vidicon format, focal distance $=100$ mm.

The flight height chosen was 1000 m and only the base was changed, so that the base-to-height ratio corresponded to a longitudinal overlap from 8 to 97.5 percent. For the large format, the base-to-height ratio was kept within normal limits; however, because of the small vidicon format (approximately 12.5×12.5 mm) it did not exceed 0.4 for the best case. This, of course, represents the first great problem of vidicon stereophotography.

For each overlap, six evenly distributed points were computed, as is the standard procedure of relative orientation. In the first stage of the statistical analysis, no errors in absolute orientation were anticipated; therefore all interest could be focused on the relative orientation itself. Each model was then computed four times:

(1) Observed image coordinates of the right picture only were changed; no camera calibration errors were assumed.
(2) Same as (1), except that calibration errors were set equal to 10 μ.
(3) Both pictures changed; no calibration errors.
(4) Same as (3), except that calibration errors were equal to 10 μ.

Figures 3–5 give the actual results of the performed statistical analysis, i.e., relative standard height errors $\sigma Z/Z$ of computed model points (positional standard errors σX and σY are not so important because they are correlated with σZ and are usually smaller, or at least of the same order). It is also interesting to notice that the influence of the assumed 10-μ calibration errors was practically insignificant, and therefore only these cases are shown.

The results for the large format, f $=100$ mm (Figure 3), agree very well with empirical limits known from conventional stereophotogrammetry. This is a good indirect verification for the correctness of the presented theoretical analysis. The results for

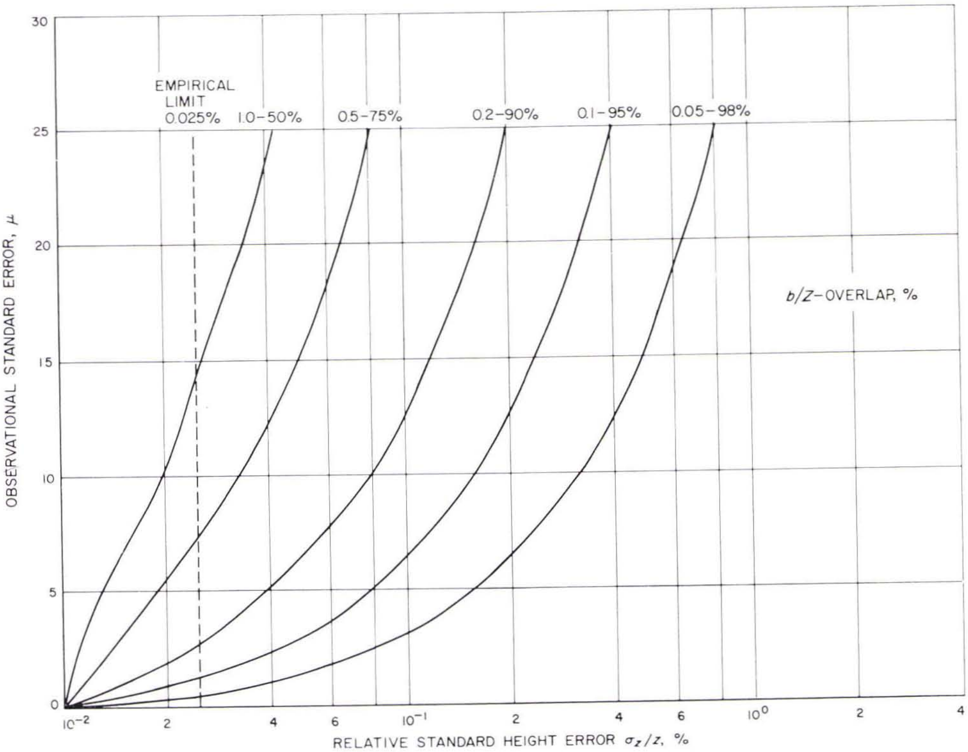

FIG. 3. Relation between observational errors, base-to-height ratio (overlap), and relative height errors: large format, $f=100$ mm.

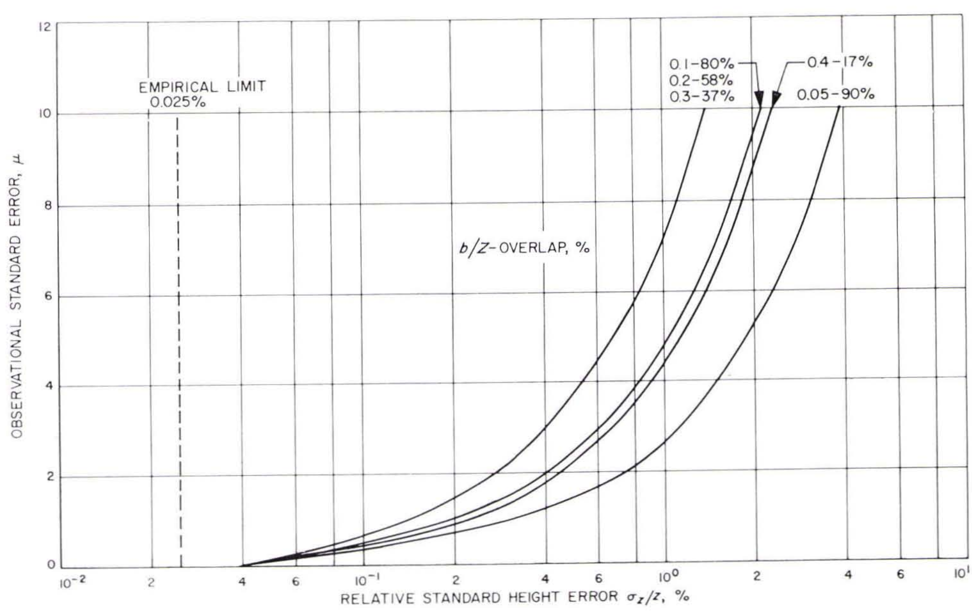

FIG. 4. Relation between observational errors, base-to-height ratio (overlap), and relative height errors: vidicon format, $f=25$ mm.

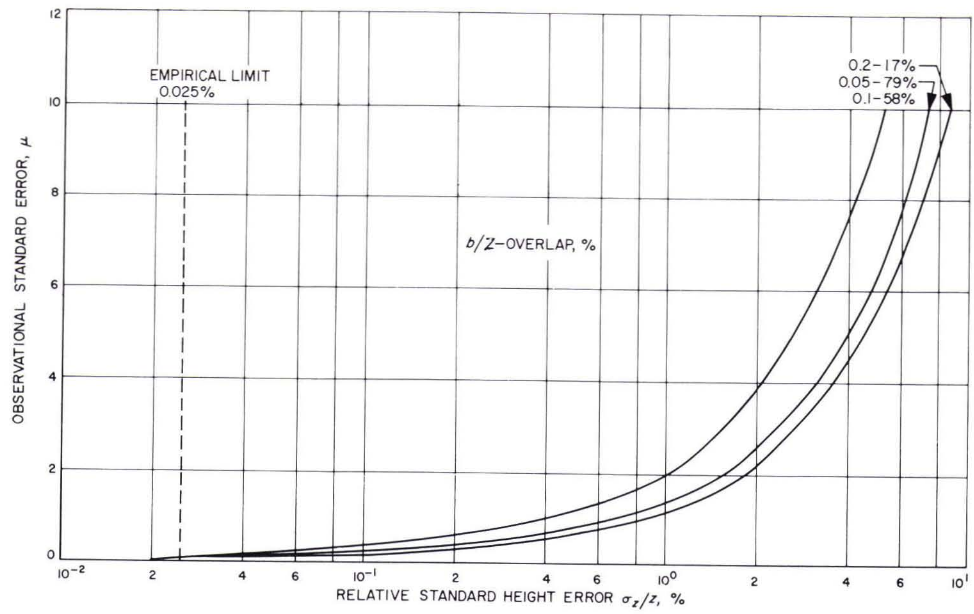

FIG. 5. Relation between observational errors, base-to-height ratio (overlap), and relative height errors: vidicon format, $f=50$ mm.

the vidicon format, $f=25$ mm (Figure 4), all lie outside the empirical limit, which is 0.025 percent, and the curves are also much steeper than they were in Figure 3. This clearly indicates the difficulties of extraterrestrial mapping problems. The results for the vidicon format, $f=50$ mm (Figure 5), show a slightly smaller influence of calibration errors than in the previous case; otherwise the curves are steeper and less favorable.

Although several models were computed for the vidicon format, $f=100$ mm, it would be of little value to show the results graphically because in most of these tests the iterative process failed to converge, or—if it did—absolutely unrealistic coordinates with excessively large standard errors were obtained. Therefore, *external* relative orientation parameters were used—their combinations are shown in Table 1—and the error analysis described above was applied to the same hypothetical models. The results obtained, which are much better than in the case of direct solution, are demonstrated in Figures 6–9.

Statistical tests for the absolute orientation error analysis have been started and

TABLE 1. COMBINATION OF PARAMETERS FOR "EXTERNAL" RELATIVE ORIENTATION

Standard errors \ *Test No.*	*1*	*2*	*3*	*4*
Rotation (radians)	0.00001	0.0001	0.001	0.003
dZ_0 base component (% of base)	0.02	0.1	0.2	0.5
Image coordinates (microns)	5	10	15	20
Principal point (microns)	5	10	25	50
Focal distance (microns)	5	10	25	50

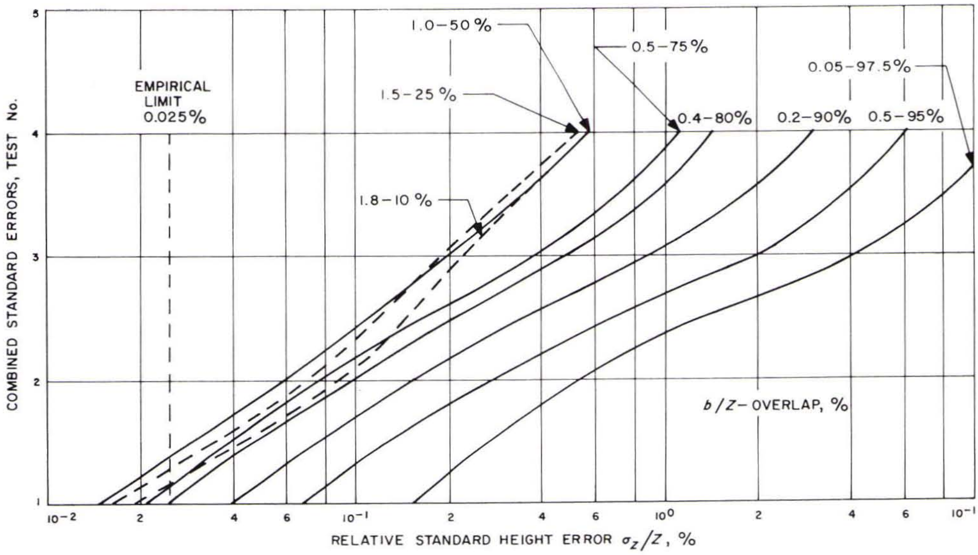

FIG. 6. Combined influence of all considered parameters on the accuracy of *external* relative orientation: large format, $f=100$ mm.

their results will be available in the near future. There is no doubt that they will also be very interesting.

CONCLUSIONS

Considering the importance of these problems, it would be rather premature to make some definite and final conclusions. However, the statistical analysis performed was sufficiently complete to give a clear general conception about the applicability of stereophotogrammetry to extraterrestrial mapping problems and to show its advantages and pitfalls.

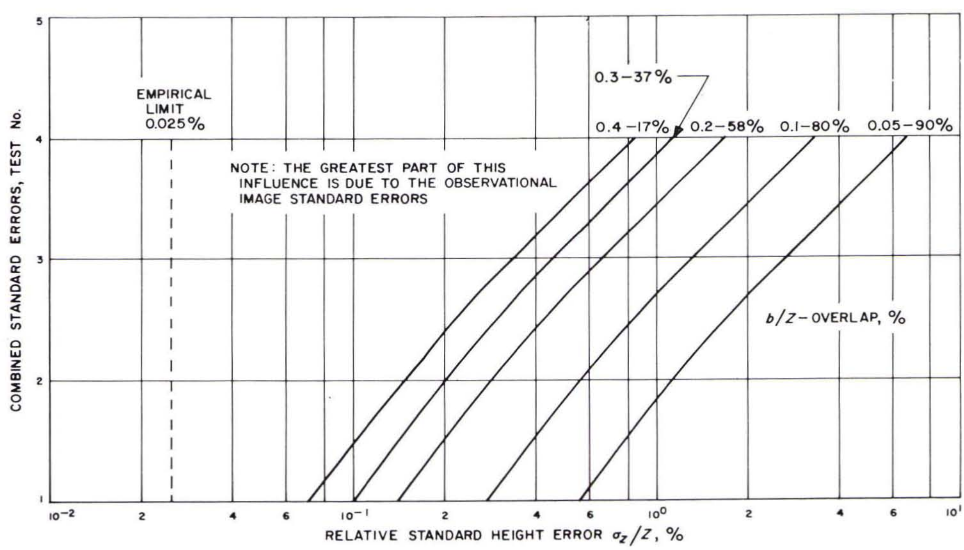

FIG. 7. Combined influence of all considered parameters on the accuracy of *external* relative orientation: vidicon format, $f=25$ mm.

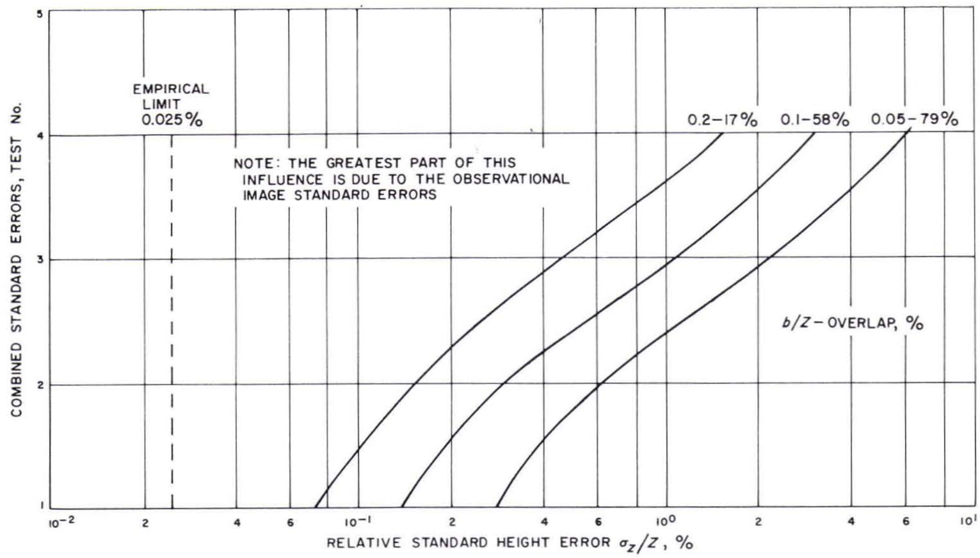

FIG. 8. Combined influence of all considered parameters on the accuracy of *external* relative orientation: vidicon format, $f=50$ mm.

Some of the important conclusions are:

(1) The derived theoretical analysis is correct and represents completely the law of propagation of errors.

(2) Because of the extremely small format of the vidicon camera system (approximate 12.5×12.5 mm), the system of normal equations required for the solution of relative orientation may become very ill-conditioned. (This can be proved by the M, N, and P numbers used in numerical analysis.) This means that even very small changes in coefficients—i.e., in observed image coordinates—result in considerable changes in computed parameters, and consequently the standard errors become very large.

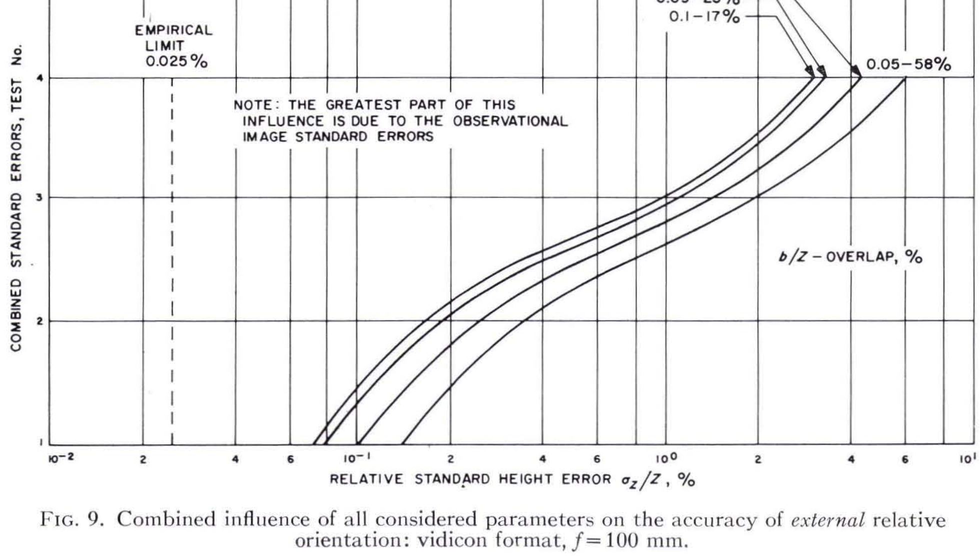

FIG. 9. Combined influence of all considered parameters on the accuracy of *external* relative orientation: vidicon format, $f=100$ mm.

Sometimes, especially for $f = 100$ mm, the system may even fail to converge (compare Figures 3–5). Therefore, instead of trying to solve the relative orientation of a photogrammetric stereopair, external orientation data should be used. The derived theoretical error analysis can be used profitably for the determination of all necessary constraints and accuracy criteria.

(3) Another possible approach would be to use a larger vidicon format. This poses an interesting research problem, the solution of which could be based on the same theoretical error analysis. It is realized that certain state-of-the-art limitations should also be considered.

(4) The importance of highly accurate measurements for all image coordinates is clearly shown (see Figures 7–9). This problem is closely related to the problem of the image quality and the calibration parameters of the camera system. Research efforts devoted to these problems would prove most rewarding.

(5) The possibility of convergent photography enabling a very high base-to-height ratio should also be investigated.

Generally speaking, the applicability of stereophotogrammetric techniques to extraterrestrial mapping problems is somewhat limited under present conditions, i.e., compared with terrestrial standards and results. However, the method itself looks very promising, and there is no doubt that after all constraints and parameter accuracy criteria are discovered and determined, it will become very effective and reliable.

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