Triplet Evaluation of Stereo-Pushbroom Scanner Data

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Abstract

Stereo registrations of the pushbroom scanners are principally used to derive height information above earth's surface.
For this purpose the coplanarity condition and the scale constraint condition are selected as the geometrical evaluation model. The time-variant exterior orientation parameters in each subdivided triplet are described by polynomials and Fourier series.
Simulation tests show that the achievable results depend on the flight conditions, the terrain ruggedness and the chosen design parameter like base to height ratio, etc.

1. Introduction

The stereo-pushbroom scanner utilizes three solid-state linear arrays of CCD detectors to gather geometrical and radiometrical information from the earth's surface. By integrating with appropriate optical system the three linear array sensors are installed into one imaging plane of known principle distance c and are oriented perpendicular to the scanner carrier heading. They are also arranged in such a way, that one of them scans forward, the second array sensor looks downward and the third one symmetrically backward. The half convergence angle γ between the vertical array and the fore array is about 22 ^{o} (Fig. 1).

Several proposed projects like

MEOSS (DFVLR / F.R.G.),

Stereo-MOMS (MBB / F.R.G.),

STEREOSAT (JPL / U.S.A.),

MAPSAT (USGS / U.S.A.)

share the briefly described imaging principle.

It can be easily seen that any ground point in a strip can be observed three times (or at least twice at the beginning and at the end of a strip). The multiple observations, as the stereo mode implies, are fundamental in the geometrical evaluations, in order to derive adjusted x_i, y_i, z_i, rectangular coordinates of each scanned terrain point.

The photogrammetric researches done for dynamic stereo imageries from the continuous strip camera [1] set an example to the geometrical analysis of stereo-pushbroom scanner data.

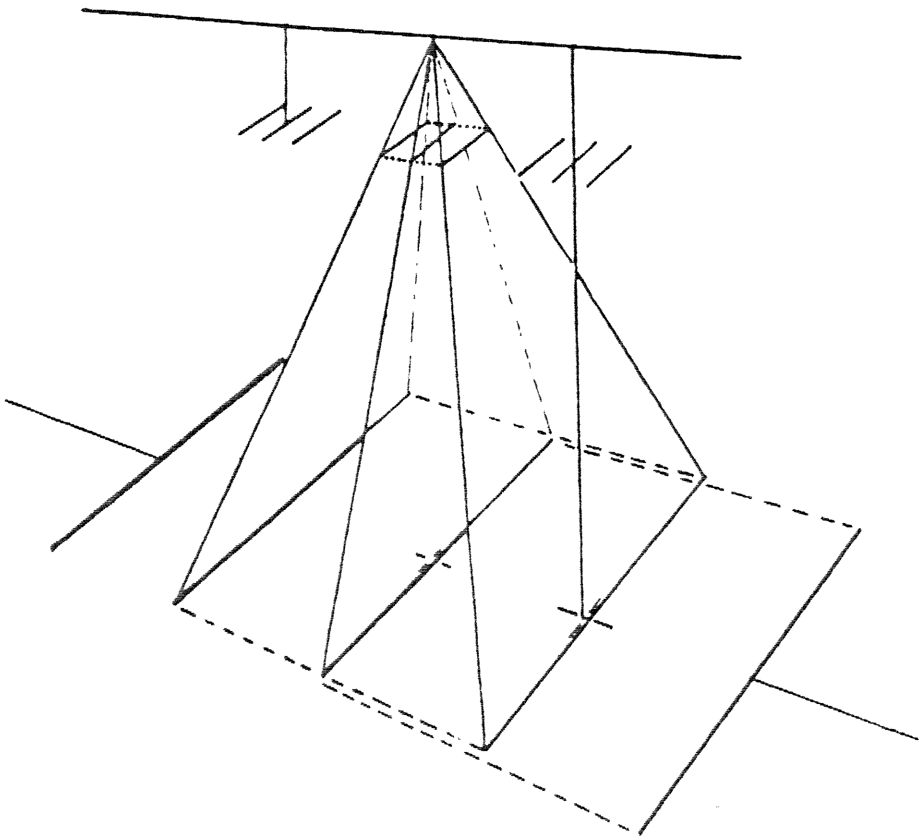

Fig. 1: Stereo Recording with 3 Linear Arrays of CCD Detectors

2. Photogrammetric Relationships

The visually measured or digitally correlated plane coordinates of conjugate image points constitute the observational data set which will be photogrammetrically evaluated.

For this purpose the coplanarity condition and the scale constraint condition are selected as the geometrical evaluation model.

a) The coplanarity condition states that the y-parallax at the model point i disappear. In other words, the ray vectors p_i', p_i'', originating from the left momentary exposure station (one prime) and from the right (two primes) are brought into intersection at the point i (Fig. 2).

$$B' \cdot (p_i' \times p_i'') = \begin{vmatrix} bx' & by' & bz' \\ u_i' & v_i' & w_i' \\ u_i'' & v_i'' & w_i'' \end{vmatrix} = 0 \qquad (1)$$

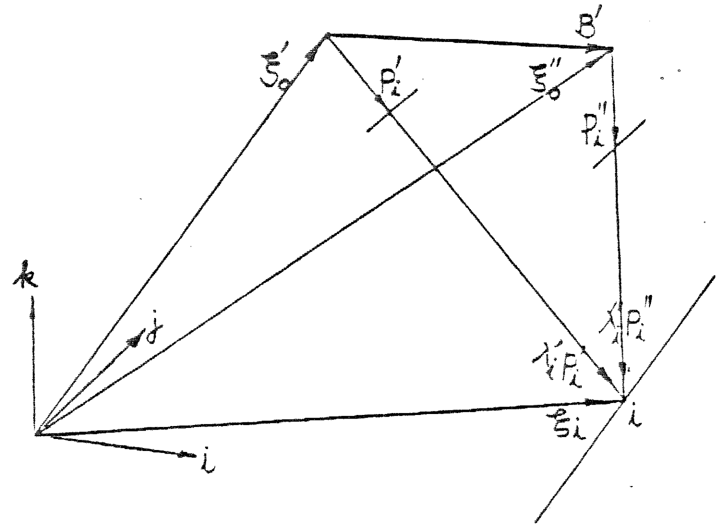

Fig. 2: Coplanarity Condition

b) The scale constraint condition demands that the two determinable scales to the model point i, viz. λ_i'' from the left vectors' triangle and λ_i'' from the right vectors' triangle, be equal (Fig. 3).

$$\begin{vmatrix} bx'' & u_i''' \\ by'' & v_i''' \end{vmatrix} \cdot \begin{vmatrix} u_i' & -u_i'' \\ v_i' & -v_i'' \end{vmatrix} - \begin{vmatrix} u_i' & bx' \\ v_i' & by' \end{vmatrix} \cdot \begin{vmatrix} u_i'' & u_i''' \\ v_i'' & v_i''' \end{vmatrix} = 0 \qquad (2)$$

One prime stands for the left instantaneous exposure station, two primes the middle exposure station and three primes the right one. u_i', v_i', w_i', ... are the rectified image coordinates, which can readily be transformed from the measured image coordinates x_i', y_i', $-c$, ... and the corresponding orientation elements ω', ϕ', κ', ...

c) Because of the dynamic movements of the stereo scanner carrier during the exposures it has been recommended in [5], [9], that the time-dependent exterior orientation parameters be modelled by polynomials and/or Fourier series, if possible, of different orders:

$$\begin{aligned} bx' &= a_o + a_1 s'' + a_2 s''^2 + \ldots & \omega'' &= d_o + d_1 s'' + d_2 s''^2 + \ldots \\ by' &= b_o + b_1 s'' + b_2 s''^2 + \ldots \quad ; & \phi'' &= e_o + e_1 s'' + e_2 s''^2 + \ldots \qquad (3) \\ bz' &= c_o + c_1 s'' + c_2 s''^2 + \ldots & \kappa'' &= f_o + f_1 s'' + f_2 s''^2 + \ldots \end{aligned}$$

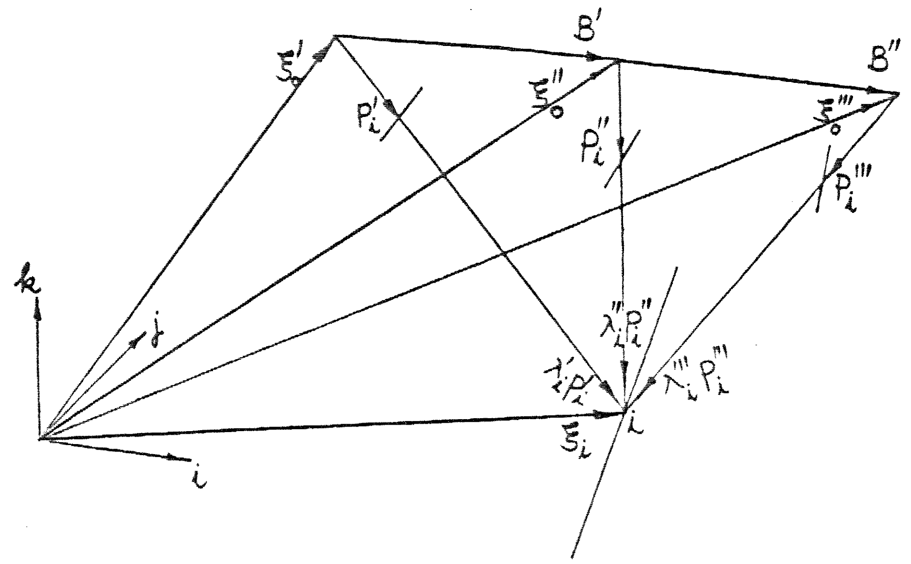

Fig. 3: Scale Constraint Condition

$$bx' = a_o + a_1 \cos\left(\frac{2\pi t''}{T''}\right) + a_2 \sin\left(\frac{2\pi t''}{T''}\right) + \ldots$$

$$by' = b_o + b_1 \cos\left(\frac{2\pi t''}{T''}\right) + b_2 \sin\left(\frac{2\pi t''}{T''}\right) + \ldots$$

$$bz' = c_o + c_1 \cos\left(\frac{2\pi t''}{T''}\right) + c_2 \sin\left(\frac{2\pi t''}{T''}\right) + \ldots$$

$$\omega'' = d_o + d_1 \cos\left(\frac{2\pi t''}{T''}\right) + d_2 \sin\left(\frac{2\pi t''}{T''}\right) + \ldots$$

$$\phi'' = e_o + e_1 \cos\left(\frac{2\pi t''}{T''}\right) + e_2 \sin\left(\frac{2\pi t''}{T''}\right) + \ldots$$

$$\kappa'' = f_o + f_1 \cos\left(\frac{2\pi t''}{T''}\right) + f_2 \sin\left(\frac{2\pi t''}{T''}\right) + \ldots$$

d) One section is conveniently defined as $c \cdot \tan(\gamma/2)$ and one triplet evaluation unit is composed of 3 sections (Fig. 4).

The argument for the aforementioned polynomials in equ. (3) is also illustrated in Figure 4.

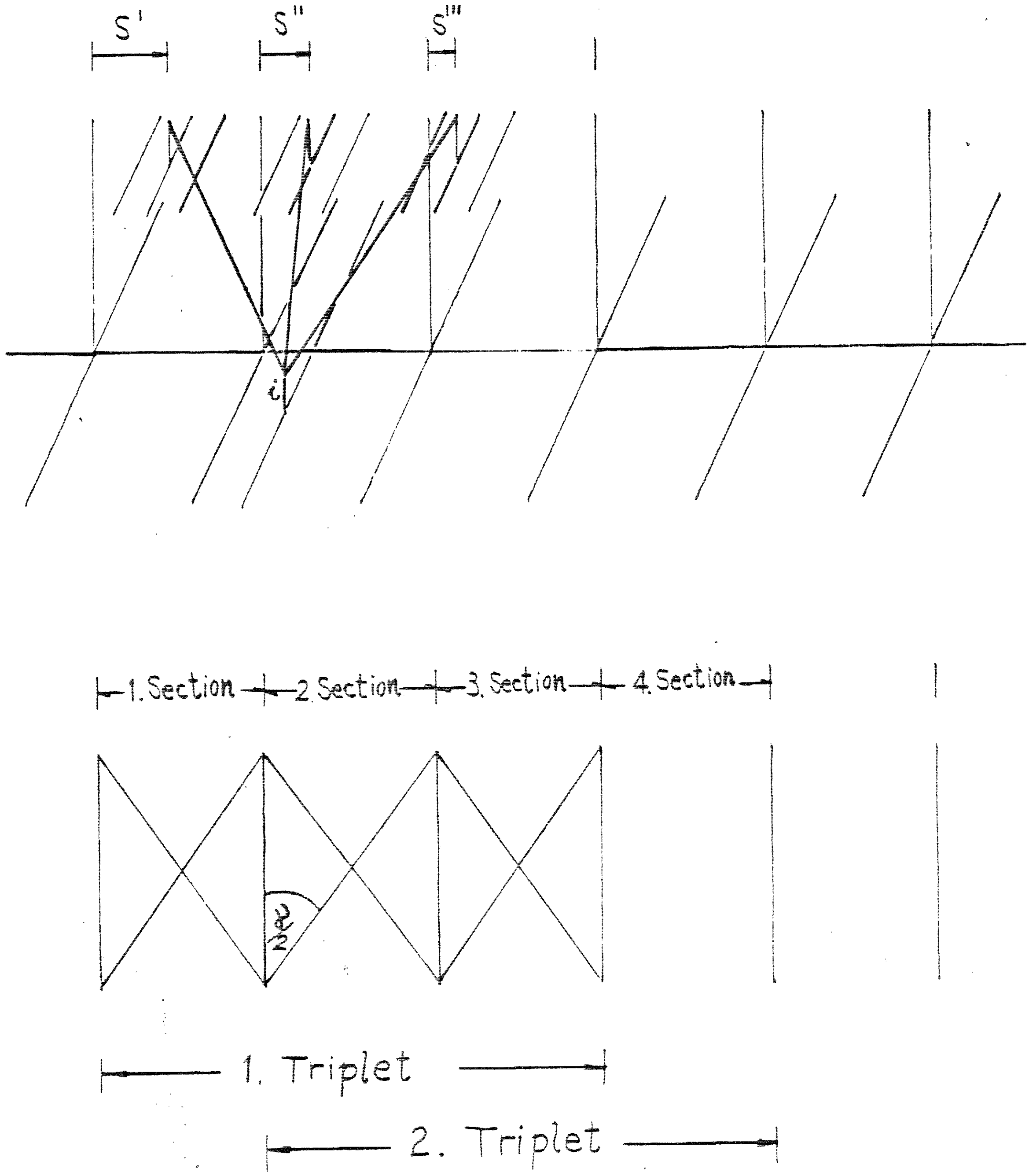

Fig. 4: Section Unit and Triplet Unit

3. Evaluation Procedures for an Imaged Strip

a) Collection of plane coordinates of conjugate image points through manual measurements, or digital simulations, or automatic correlations

b) Determination of the polynomial coefficients for exterior orientation parameters in each section using the least squares adjustment:

b.1) The first triplet unit consists of sections 1, 2, 3 (Fig. 4). Since the applied coplanarity condition (1) and the scale constraint condition (2) for each conjugate image point are nonlinear, the adjustment is based upon the corresponding, linearized equations (4) and is subjected to iterations. Additional linearized connection conditions (5) at the section interfaces should also be set up to make sure that the orientation curves run smoothly through the interfaces, as evidenced in Fig. 6.
Altogether these lead to the computation task characterized as the least squares adjustment with conditions and constraints among unknowns. The linearized matrix equations are

$$\underline{P}\ ; \qquad \underline{B} \cdot V + \underline{A} \cdot X = L \tag{4}$$

$$\underline{C} \cdot X = W \tag{5}$$

$\underline{P}$: a priori weight matrix
$\underline{B}$, $\underline{A}$, $\underline{C}$: coefficient matrices
V : residual vector of observed conjugate image coordinates
X : unknown polynomial coefficients vector
L, W : column vectors of constants

The least squares solution can then be expressed as follows:

$$X = X_o + \delta X$$

$$X_o = \underline{N}^{-1} \tilde{L} = (\underline{A}^T (\underline{BP}^{-1}\underline{B}^T)^{-1}\underline{A})^{-1} \cdot \underline{A}^T (\underline{BP}^{-1}\underline{B}^T)^{-1} L$$

$$\delta X = \underline{N}^{-1}\underline{C}^T (\underline{C}\, \underline{N}^{-1} \underline{C}^T)^{-1} (W - \underline{C}\, X_o)$$

b.2) The second triplet unit contains sections 2, 3, 4. The already adjusted orientation parameters in the beginning section (section 2) from the foregoing triplet unit (the first triplet) are invariably taken over and will not be changed in the current triplet adjustment.

b.3) The following triplets are treated in the same manner as was done for the second triplet.

c) Using the adjusted orientation parameters the spatial intersection procedure is carried out to obtain a model strip (for instance, see Fig. 7).

d) With the help of ground control coordinates the three-dimensional similarity transformation parameters Λ, X_o, Y_o, Z_o, Ω, Φ, κ are calculated, so that the model strip can now be absolutely oriented to the desired control coordinate system.

e) Analysing the coordinate deviations at control points covariance functions can be derived, which will then be referenced in the linear prediction process for the available ground check coordinates. The linearly predicted coordinate values are the final results from which quadratic means as accuracy measures are derived for the position as well as the height.

$$q_{xy} = \sqrt{\frac{s_x^2 + s_y^2}{2}} \quad , \quad q_z = s_z$$

s_x, s_y, s_z: empirical standard deviations in x, y and z at existing check points

q_{xy}, q_z : quadratic means

4. Simulation Experiment

a) One example of the given digital terrain models (Fig. 5)

Number of grid points	:	133 (19 x 7)
Grid separation in x and y	:	200 m
Number of ground control points	:	60

other chosen simulation parameters:

focal length	:	24 mm
flying height above ground	:	1200 m
image scale	:	1 / 50 000
detector size in image space	:	16 µm
pixel size in object space	:	0.8 m
instantaneous field of view (IFOV)	:	0.67 mrad.
aircraft velocity	:	52 m/sec.
scan frequency	:	65 Hz.

For further information about base-to-height ratios and flight conditions references are made to Fig. 9 and Fig. 10.

b) The curves for accuracy results are accompanied with pixel unit scales positioned to their left and to their right. The abbreviations used in the top left legend field serve to distinguish the investigated cases (curve types):

DGM means terrain type; FLUG means flight condition; GAM means convergence angle between fore and aft array; PLNM: 3 means polynomials with 3 coefficients; DELTA H means elevation difference on the ground.

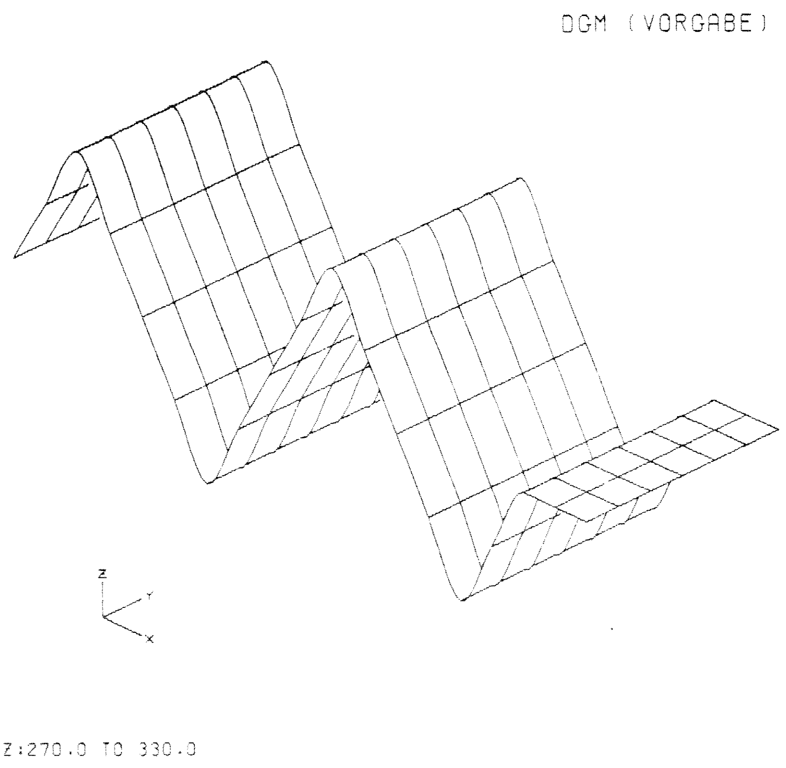

Fig. 5: (known) Digital Terrain Model

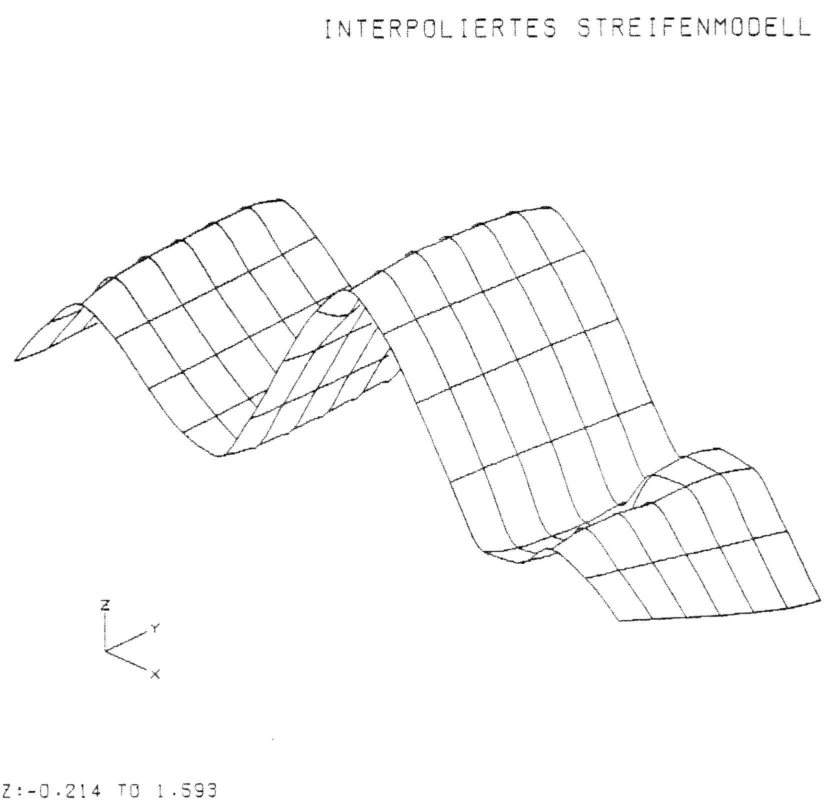

Fig. 7: Model Strip Computed from the Spatial Intersection Procedure (cp. Fig. 5)

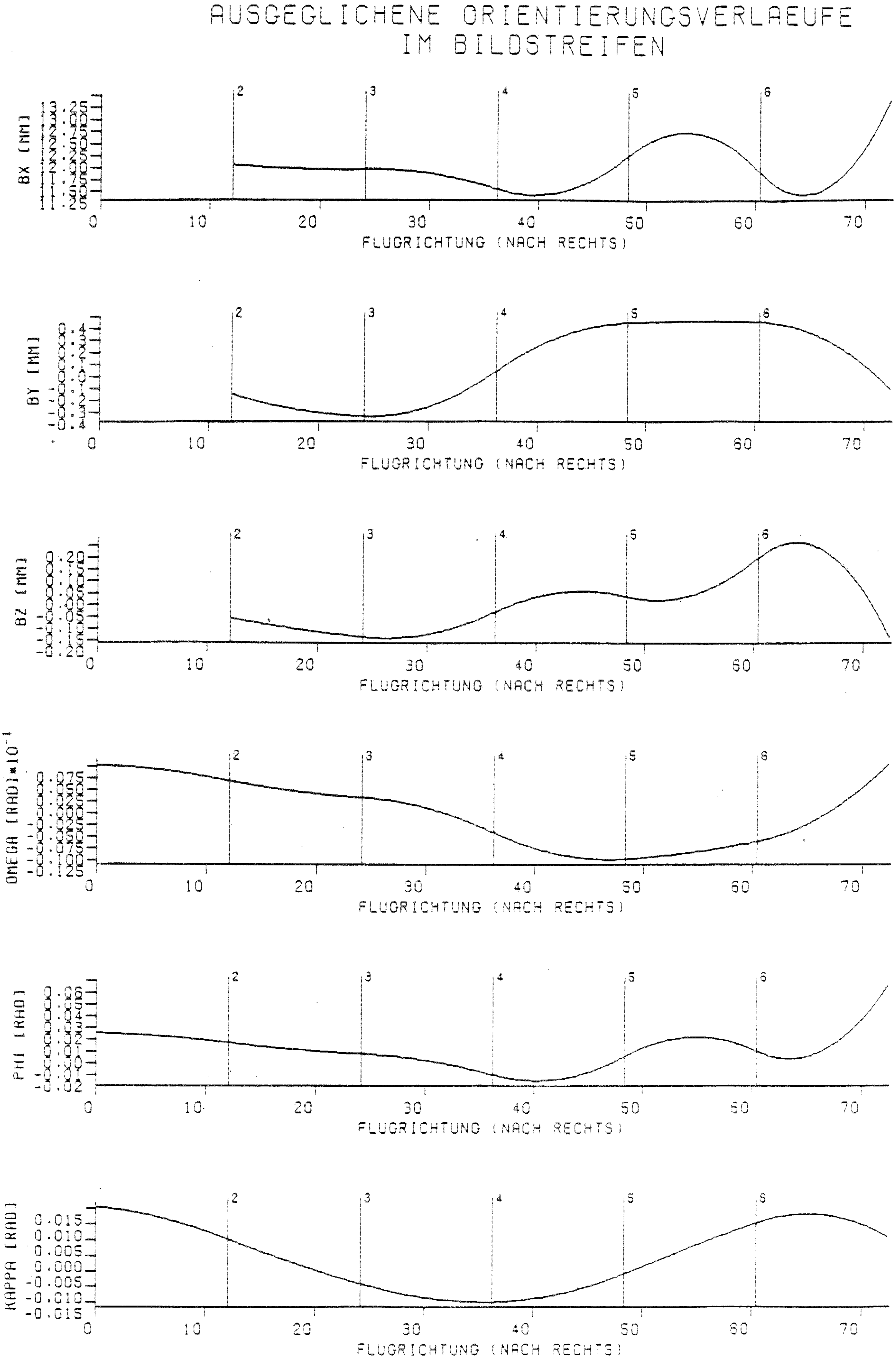

Fig. 6: Adjusted Exterior Orientation Parameters .

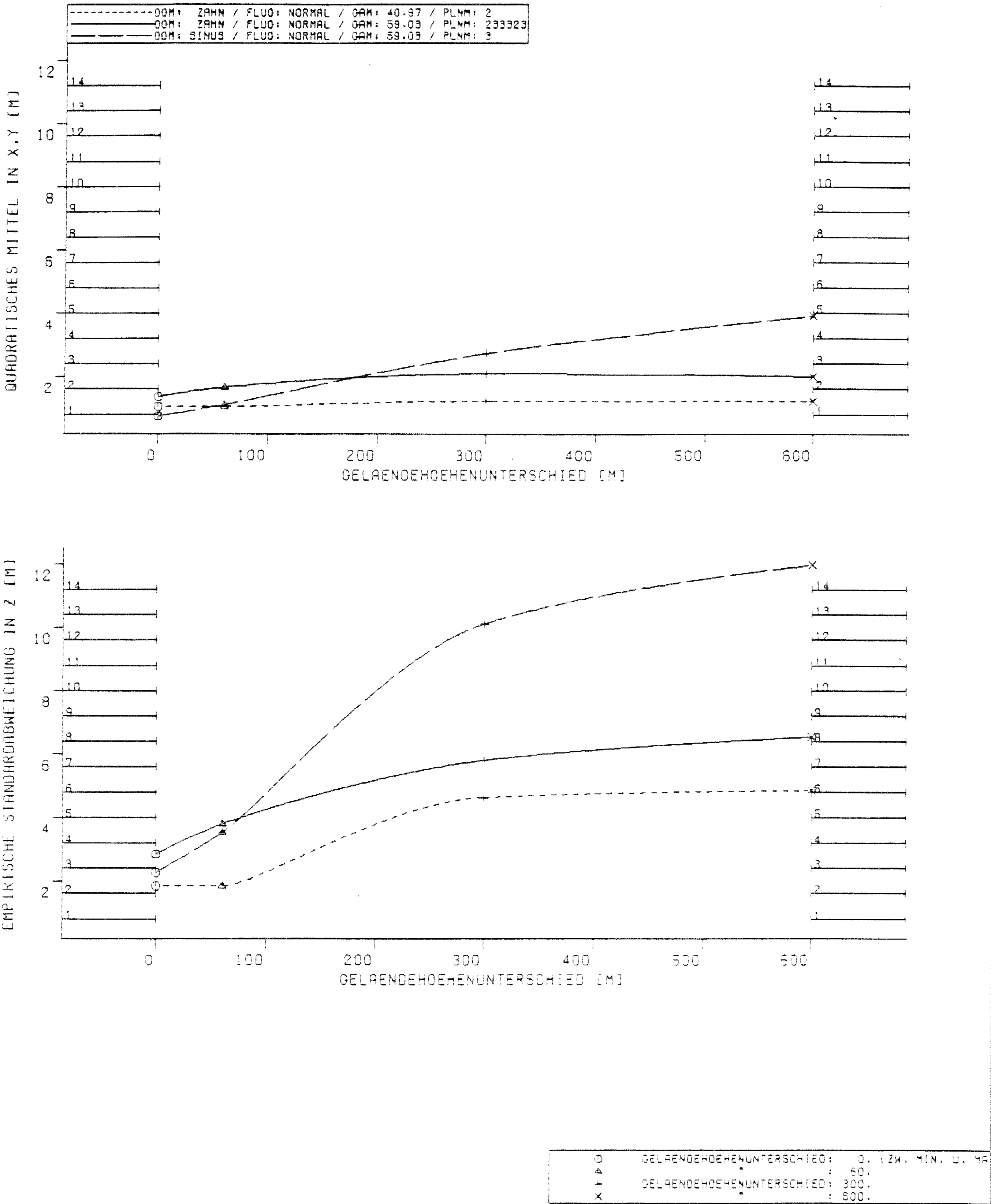

Fig. 8: Quadratic Means as Functions of Terrain Ruggedness
(characterized by elevation difference)

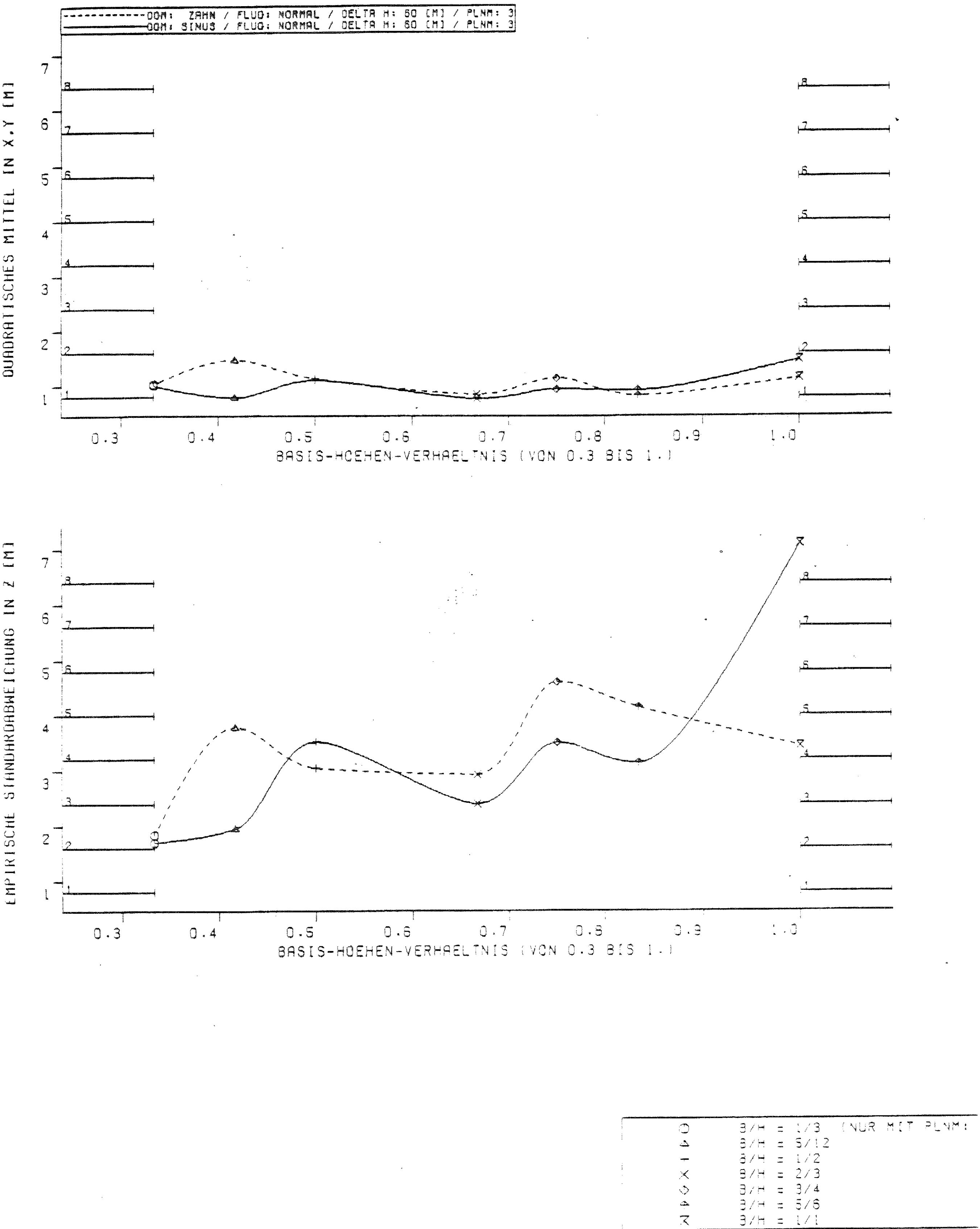

Fig. 9: Quadratic Means as Functions of Base-to-Height Ratios
(comparable to Convergence Angles)

Flight conditions are arbitrarily simulated through Fourier series with one cosine and one sine term. The (pre-)selected amplitudes and periods are summarized except for the case Ideal:

$$\text{any orientation parameter} = a \cos\left(\frac{2\pi t_j}{T}\right) + b \sin\left(\frac{2\pi t_j}{P}\right)$$

Flight Condition		X_0[m]	Y_0[m]	Z_0[m]	ω [gon]	ϕ [gon]	κ [gon]
Stable	a	1.4	-1.9	-0.9	0.	0.1	0.1
	T[sec]	220	230	240	320	240	220
	b	14	19	9	0.5	-1	-1
	P[sec]	120	130	140	220	140	120
Variant	a	5	10	5	0.2	0.5	0.5
	T[sec]	69	69	79	89	79	69
	b	1	2	1	0.	0.1	0.1
	P[sec]	7	7	7	7	7	7
Normal	a	14	19	9	0.5	1	1
	T[sec]	69	69	79	89	79	69
	b	0	0	0	0	0	0
	P[sec]	•	•	•	•	•	•
Un-stable	a	-20	-20	20	- 0.4	2	2
	T[sec]	90	100	110	210	110	100
	b	5	5	5	0.1	-0.5	0.5
	P[sec]	30	30	40	70	40	30

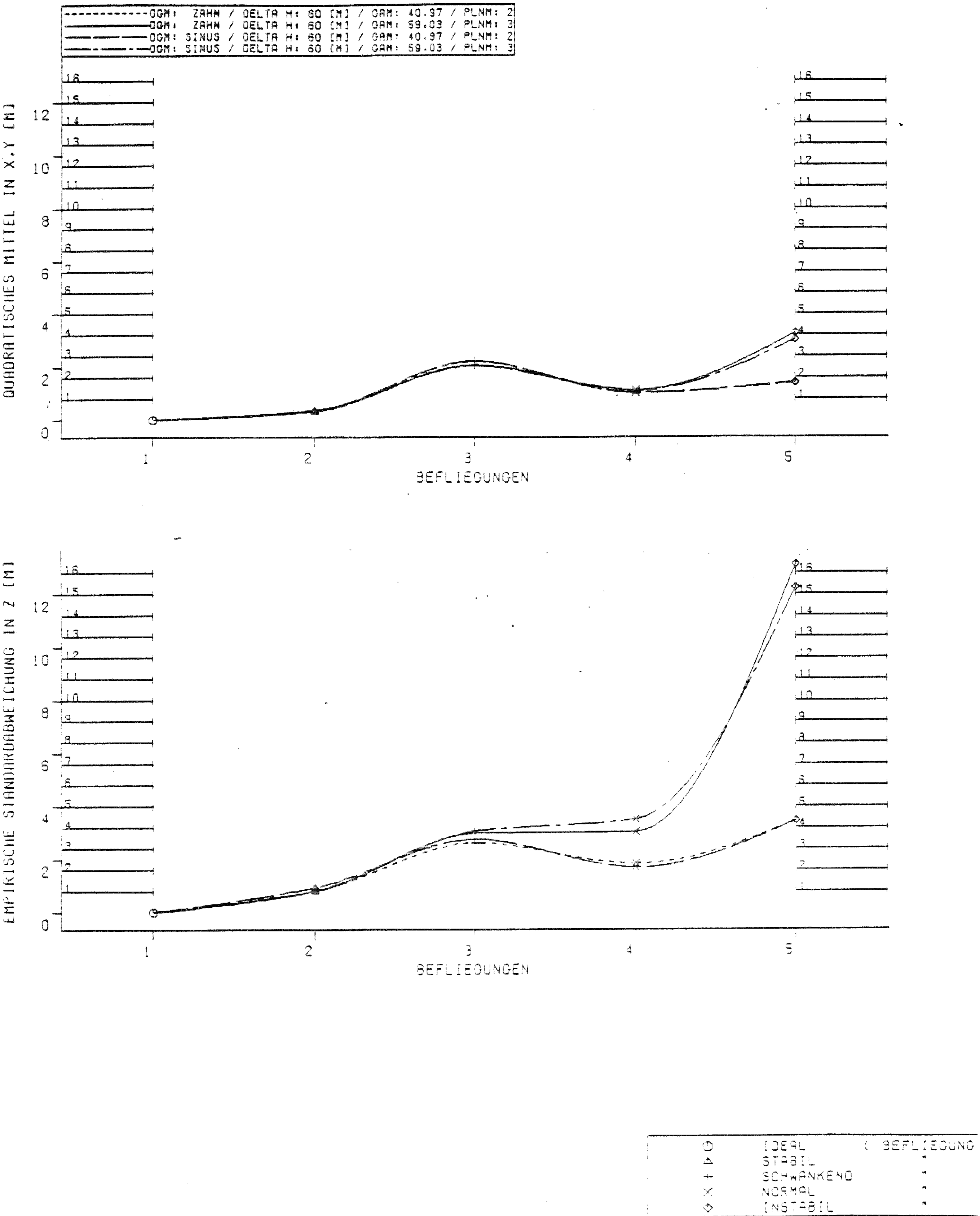

Fig. 10: Quadratic means as functions of Flight Conditions

5. Remarks

a) The simulation results achieved till now limit itself to the aerial photography. Generally, the planned navigation for aerial flight will be more disturbed. In extreme the ratio of elevation difference to flying height reaches 0.2 to 0.4.

b) The triple channel recording offers the opportunity, that all the exterior orientation parameters along the flight be determined. During the simulations there has been no numerical difficulties. However based on the diagrams of adjusted orientation parameters in Fig. 6 it can be clearly seen, that certain correlation exists between bx and ϕ. The accuracies at check points would surely be improved, if either bx or ϕ were treated constant in the least squares adjustment.

c) If in-flight registrations (aircraft velocity, heading, APR data ... and so forth) are made available, they can serve as auxiliary control information. The composite coordinate determination should show accuracy improvements, provided that the corresponding weights of hybrid data are duely taken into account.

d) The fact that the exterior orientation parameters are modelled by polynomials is apparently an endeavour to reduce the number of unknowns in each triplet, thus in the entire strip. On the other hand, if the six orientation parameters of every scan line are explicitly asked for, it would normally be impossible to find sufficient conjugate image points (except for the automatic digital correlation techniques with the highest degree of operating security) to yield the required redundancy for the whole adjustment. Pseudo-observation equations are needed. The published Gauss-Markov-Process from [2] can then be applied to each scan line to statistically enhance the ties among some neighboring scan lines.

6. References

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