ACCSIM module 2 : Simulation of Camera Elements (flight parameters)

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1. PROBLEM DESCRIPTION

The ideal camera elements for a pair of overlapping aerial photographs are $\varphi' = \varphi'' = \omega' = \omega'' = \kappa' = \kappa'' = 0$, by = bz = 0, and bx should be a function of the specified forward overlap and flight height above ground.

Due to a number of perturbating factors, actual camera elements are different from the specified ideal ones. The camera elements bz, φ and ω relate directly to the height and attitude of the aircraft along the survey flight line, whereas by, κ and bx are a function of the position and attitude of the aircraft and of the camera operator's measures. In addition, bx is also directly affected by the height of the terrain. Consequently, one can differentiate between the "flight parameters" pertaining to the aircraft, and the "camera elements" pertaining to the camera. The difference between the two consists of

the operator's influence. If a stabilized mount is used, then the relation between flight parameters and camera elements will be different for φ, ω and $\varkappa$.
The use of an automated or semi-automated navigation system (Doppler or Inertial System, resp.) will have an influence on both the flight parameters and the operator's action. The deviation of the actual from the ideal camera elements has an effect on the photogrammetric process. As an example point selection, errors of plotting instruments, neglect of higher order terms in linearizations of projective relations might be mentioned. So far, however, not much attention has been paid to these dependences. Project 'Accsim' provides a welcome opportunity to fill this gap. In order to do so, a mathematical model has to be established for the deviation of the actual from ideal camera elements, and a simulation programme provided within project 'Accsim', to generate camera elements.

The degree of complexity of the model for those elements should be adjusted to its purpose. Preliminary analysis led to the conclusion, that the model should essentially incorporate the randomness of the camera elements and their auto-correlations in subsequent exposure stations, in a range of a few seconds up to half a minute in time between subsequent exposures with a frame camera. According to the above preliminary analysis cross correlations among different camera elements for a single exposure station are negligible. However, the model should preferably also enable the study of camera elements with respect to continuous remote sensing imagery. For this purpose, the interval between successive exposure stations approaches zero.

Summarizing, the problem consists of defining a mathematical model, and algorithms for simulation, of the aircraft's attitude and position along an individual survey flight line. The relation between camera elements and flight parameters are studied separately, and a separate program-routine must be provided for conversion of flight into camera parameters.

2. INFLUENCING FACTORS

The factors influencing the parameters of a survey flight are listed in table 1. An analysis of interrelations among these factors reveals, that the actual flight parameters are created in an extremely complex physical process.

There are long as well as short term perturbances. The steadiness of the aircraft decreases with increasing altitude and speed. The atmospheric turbulences reduce in strength and frequency of occurrence at greater heights. Turbulences produce mainly short term perturbations not affecting the flight line as a whole.

The heading of the aircraft is generally measured by a compass. This makes the system sensitive to changes of magnetic declination, if flight lines are of greater length.

A good autopilot, if available, operates like a good human pilot, as far as keeping the heading constant and controlling the aeroplane's attitude and altitude. The reaction time and damping characteristics of an autopilot depend on the particular instrument and its adjustment. There is a difference whether it is adjusted for good passenger comfort or for optimum control in survey flight. The pilot resp. autopilot is responsible for controlling the aeroplane's azimuth (heading resp. yaw), attitude and altitude.

At present, most of all survey flights are controlled manually. In a few cases Doppler navigation is applied. Inertial systems have been used only for some very special projects.

The crew operating the aircraft has a great influence on the flight line as a whole, and cannot control the short term perturbations so well. An important aspect of influencing the flight line consists of the type of navigation which is applied (e.g. visual or Doppler). An important task of the crew, in particular of the camera operator, is the regulation of the exposure cycle, or bx, which is a function of aircraft speed and terrain relief.

1. Aircraft
    - Steadiness
    - Speed
    - Altitude

2. Instrumentation
    - Compass
    - Autopilot, its characteristics in reaction time and damping
    - Doppler
    - Inertial guidance

3. Crew
    - Manual piloting
    - Reaction of pilot
    - Overreaction of pilot
    - Visual navigation
    - Drift measurement - frequency and accuracy

4. Atmosphere
    - Change of wind
    - Turbulences due to air instability
    - Turbulences due to relief
    - Up and down draft due to relief

5. Terrain
    - Recognition
    - Relief
    - Magnetic variation

Table 1. Factors influencing the flight parameters.

A component of the navigator's activities is the measurement of drift angle at regular intervals. Change of drift, if observed, leads to a change of heading indicated by the navigator. The fewer the number of check points on the ground the higher the requirements for reliable drift values.

Change of drift results as a change of wind direction or speed and influences by and κ. Atmospheric turbulences, however, result from the local instability of the atmosphere or are propagated from the ground as a result of relief and have an influence on φ, ω and κ. Relief also produces longer term up and down drafts in the atmosphere and influences bz. Terrain relief affects the condition of the atmosphere and bx. But the terrain itself also affects the result of visual navigation. If insufficient details can be recognized or if there are no maps available, then the flight line might show a long term lack of straightness.

3. MODELS FOR SIMULATION OF FLIGHT PARAMETERS

For the purpose of analyzing the photogrammetric process, study of the flight parameters is a secondary problem. This is due to the fact that deviations from ideal parameters are well accounted for in the data reduction procedures, so that only second order effects of flight parameters can propagate into the results of photogrammetric projects. This allows for a greatly simplified model of the parameters, as compared to physical reality or the requirements of aeronautical engineering.

This consideration led to a preliminary study and comparison of four alternative models, namely:

- arbitary functions
- piecewise polynomials
- damped disturbances
- feedback or autoregressive model

The entities to be modelled are the position (X, Y, Z) and attitude (φ, ω, κ) of the aircraft along a survey flight line. These six parameters can either be dealt with directly, or actual study might refer to (φ, ω , Drift, Speed, Heading, Z). From this group the former can be directly computed. The second group allows for an original relation to be established between wind and drift, heading and compass, so that the study should be based on the second group. X, Y coordinates result as a function of drift, heading and speed.

3.1 Arbitrary Functions

Non-linear functions, including trigonometric terms, and defined on an infinite range for the independent variable, could represent each of the three attitude and three positional flight parameters. Experiments would have to show, which functions and which function parameters produce flights with the same statistical properties relevant for photogrammetric problems as really observed flights. These statistical properties concern the distribution of the camera elements and their correlation between successive exposures.

An advantage of this approach consists of the fact that the function is continuous, has an infinite range of definition, and does not require much computation time.

A disadvantage is the fact, that the model under discussion does not relate to physical reality, but is completely abstract: observed realizations of non-mathematical random functions are represented by a continuous function. The approach is therefore rather inflexible and depends fully on observed flight parameters.

3.2 Piecewise Polynomials

A very similar approach is to represent the flight parameters by a hierachy of piecewise polynominals. As an example, each parameter could be represented over a distance of 200 km by a hierachy of 631 polynomial pieces of 3rd order

1	polynomial	of	200 km
5	"	"	40 km
25	"	"	8 km
100	"	"	2 km
500	"	"	400 m

eneration of polynomial pieces is by generation of function values and tangents at the boundaries of adjacent pieces. Statistical properties of these values would have to be determined by trend analysis of actual measurements, or by simply comparing simulated cases with actual ones, until appropriate parameters are found for the model.

An advantage of this approach consists of the fact that smoothness of the generated functions can be explicitly controlled through the generated tangents, frequencies through the subdivision into a hierarchy of polynomial pieces. Computation can be fast, since no trigonometric functions have to be evaluated. Long and short term correlations can well be separated and simulated.

The disadvantage is again that one does not model physical reality and that the range of definition of the piecewise function is limited.

3.3. Damped Disturbances

A model is formulated for the frequency of occurrence, amplitude and damping of perturbations of the ideal flight parameters. At random locations along the flight path, a disturbance is produced of the form

$$\text{dist.} = A \cdot \cos(\xi \cdot X + \eta) \cdot e^{-Bx} \qquad (1)$$

with A = amplitude, ξ = frequency, η = phase, B = damping factor,
x = independent variable.

The advantage of such an approach is that it is a model of physical reality, especially as far as attitude parameters are concerned.

The disadvantage is that the range of definition of the resulting function is limited and computation might be somewhat expensive through evaluation of trigonometric and exponential functions.

3.4 Feedback or Autoregressive Model

In this approach, not the flight parameters themselves, but their 1st derivatives with respect to the independent variable are considered. It is based on well known feedback or statistical autoregressive models.

In general, the change f'(x) of a certain flight parameter f(x) results at x = i from a differential equation, which can in general be written as:

$$f'(x)_{x=i} = f'(x)_{x=k} + F\left\{f(x),\ f'(x),\ f''(x)\ \ldots\right\}_{x=k} + L.R \qquad (2)$$

The change f'(x) of a flight parameter at a certain x = i is a function of previous changes f'(k), rate of change f"(k) and integral over changes, thus function value f(i). R is "noise", normally distributed with mean zero and variance 1. L is a scale factor for the noise.

The particular advantage of this approach over previous ones is that it represents a model of physical reality, in which random perturbations occur, whose effects are damped and compensated by corrective actions of either the pilot, autopilot or the inertia of the aircraft.

A disadvantage might in the first instance be expected from the computation time. Preliminary considerations showed, however, that the computational efforts are not excessive at all, not even in comparison to the previous models.

Realization of the autoregressive model can be on the basis of observed flight parameters. But it can also be on the basis of the relation between the influencing factors of chapter 2 and equation (2). These relations are to some extent qualitatively known through navigation and piloting experience.

Some experiments with the autoregressive model have already been carried out by Mr. Kunji. Examples of generated flight parameters and in-flight recordings of actual parameters are shown in figures 1 and 2. Each generated function consists of 800 discrete points and represents 4 min of flight. So parameters are generated in this example at an interval of .3 sec. of flight. Computation time was .2 ms/point. The overall computation time can be considerably reduced through an increase of the interval of generation.

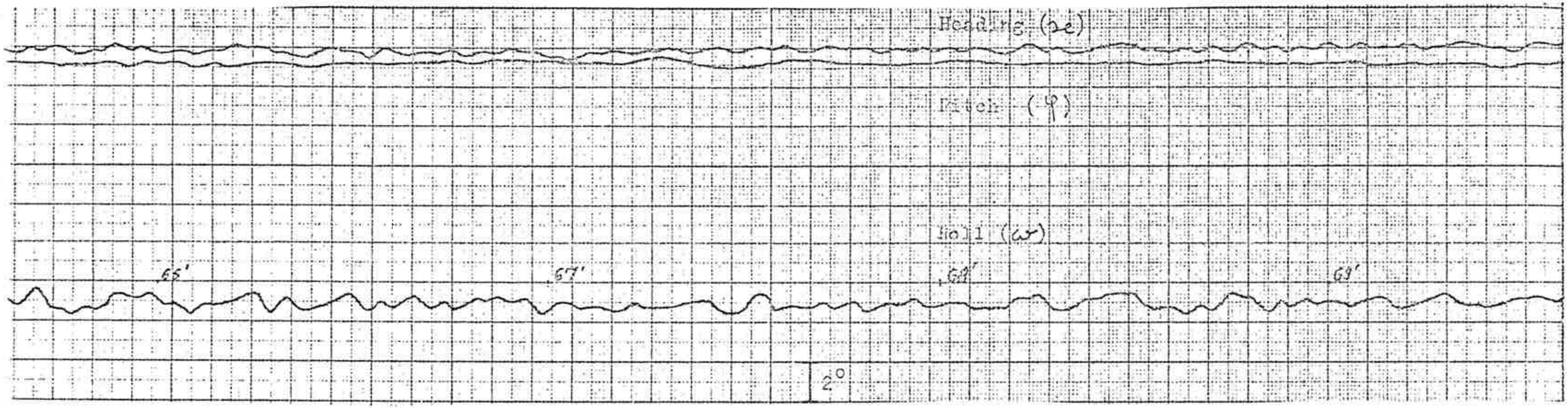


Fig. 1. Measurement of φ, ω, $\varkappa$ aboard a Transall C160 aircraft, at 8 km height, 400 km/h speed.

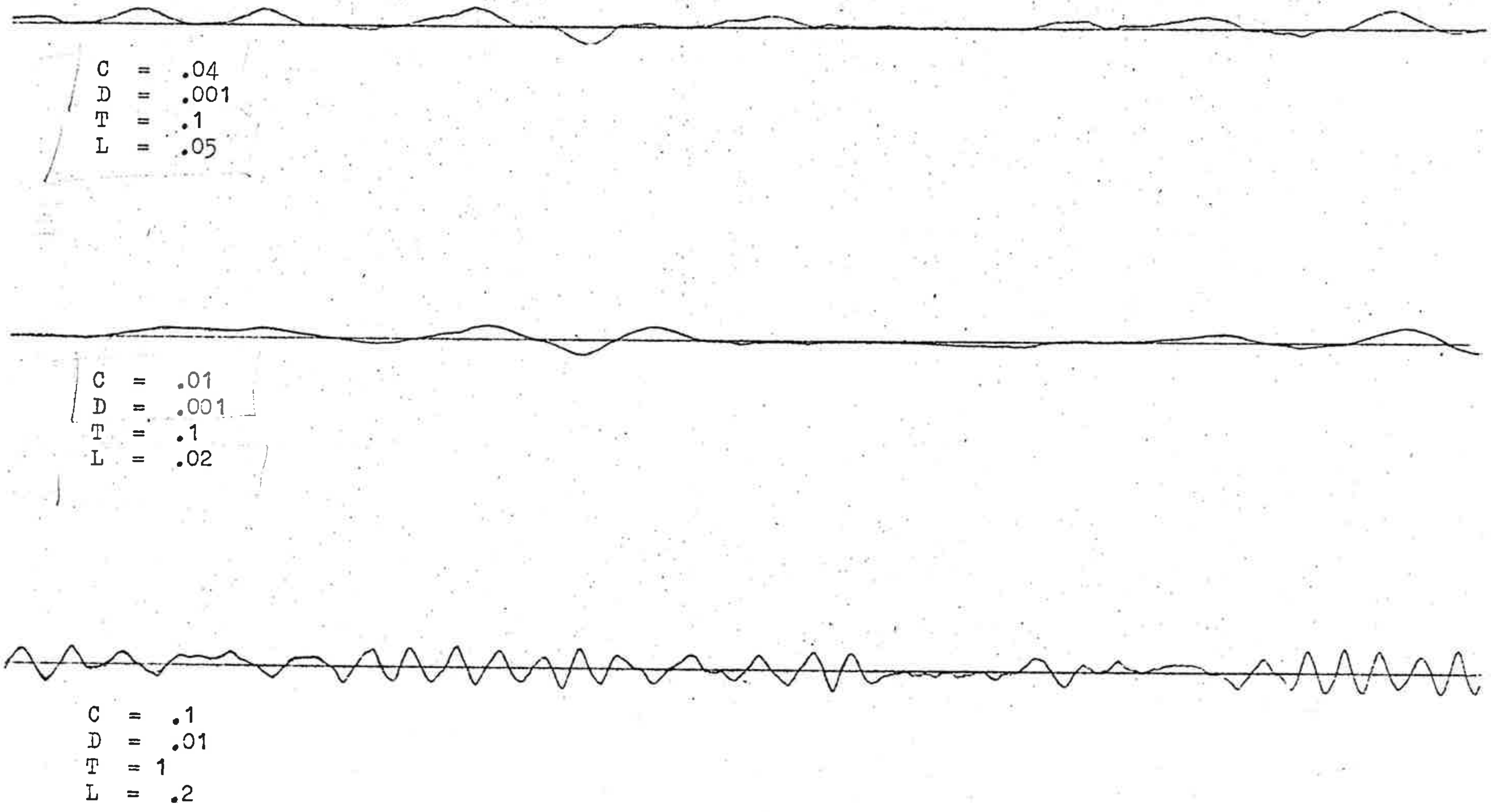


Fig. 2. Simulated $\varphi, \omega, \varkappa$, same scales as fig. 1.

The feedback function used for the example of figure 2 was:

$$f'(x)_i = f'(x)_{i-1} - D.f^3(x)_{i-1} - C.f'(x)_{i-1} . 1/(T + f^2(x)_{i-1}) + L.R$$

The particular values of the coefficients D, C, T and L are indicated in figure 2. Experimentation with different feedback functions is continuing.

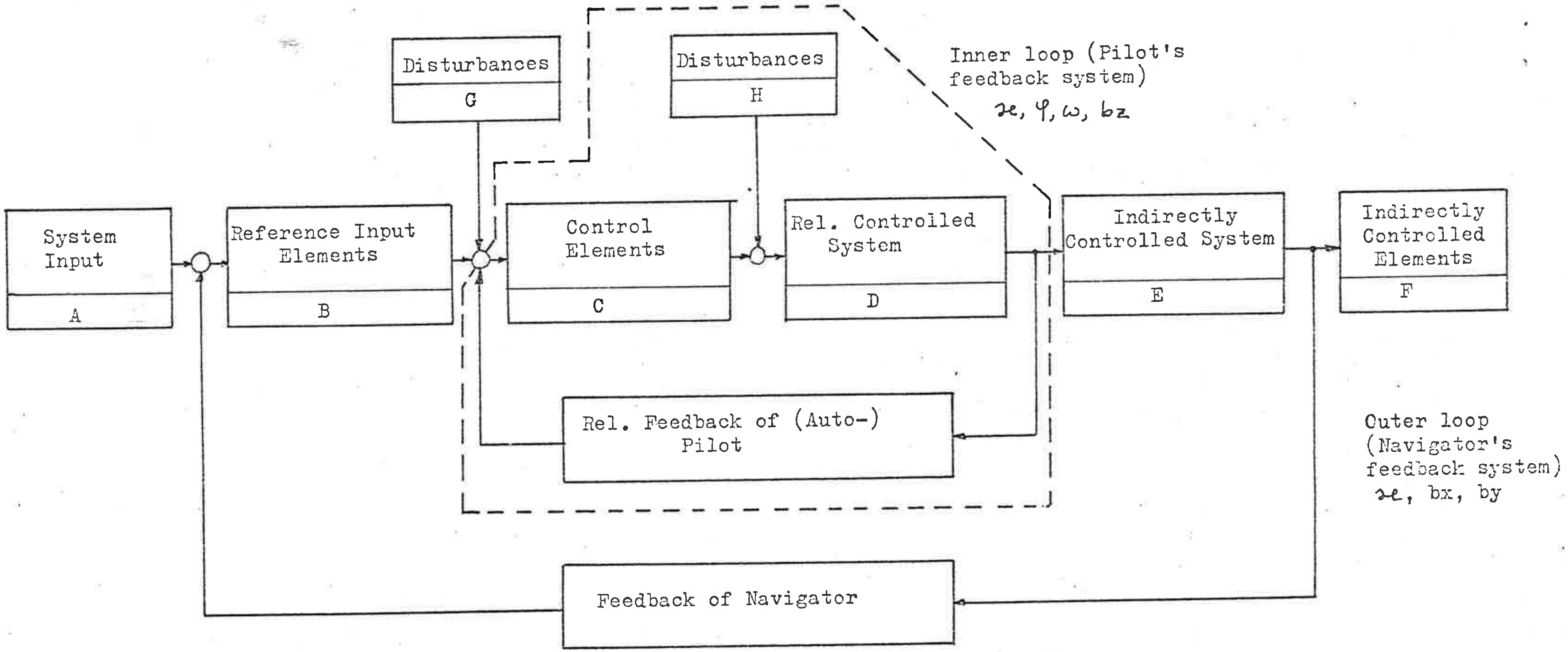
4. INPUT - OUTPUT

The input to the simulation of flight parameters should consist first of all of the flight plan, and then of a list of data concerning the influencing parameters of table 1. It is proposed that a number of classes of aircraft types, speed, height, wind, frequency of turbulences, proficiency of crew etc., and type of navigation be defined.

The simulation program itself then translates these specifications into the coefficients of the simulation model. The flight plan provides initial position (eventually in geographical coordinates) and attitude data for, and the length of, a flight line to be generated.

Output of the simulation program should consist of the three attitude and three position parameters (eventually in geographical or local cartesian coordinates) of the aircraft along the flight line. This is then input to a module converting flight parameters into camera elements. The module incorporates the camera operator with its corrective measures concerning camera levelling, drift and bx.

Apart from the overall input and output, there are a number of feedbacks occurring within the simulation program. Figure 3 illustrates the feedbacks as they would be incorporated in a simulation based on an autoregressive model. Two feedbacks are identified: one through the (auto-)pilot, and one through the navigator. It should be realized at this point that the feedback cycle of the pilot is at a much higher rate than the one for the navigator, since the pilot is correcting continuously, whereas the navigator is giving instructions at longer intervals.



A: Flight plan.

B: Instructions to pilot from navigator.

C: Steering of pilot.

D: Behaviour of aircraft as measured and controlled by pilot, using instrument board.

E: Behaviour of aircraft as measured and controlled by navigator, through observation of Earth's surface.

F: Output.

G: Disturbances affecting outer loop with navigator (position identification error, wind changes etc.)

H: Disturbances not affecting navigator but measured or sensed by pilot (atmospheric turbulences, height variations)

Fig. 3. A 2-loop feedback control system for navigation of an aircraft with pilot and navigator, with terminology of "Reference Data for Radio Engineers", ITT, N.Y. 1963

Output of survey flights which would in normal practice be subject to rejection due to excessive curvature of flight lines and resulting gaps, are of no interest in the present system. Since such cases are always reflown, it is sufficient to produce only imagery fulfilling specifications of the flight plan. Eventual consideration of catastrophic deviations of flight parameters is only required in the generation of a different film distortion etc. due to reflights under different conditions.

5. REQUIRED DATA

In order to establish the relation between the influencing factors and the coefficients of the model of the flight parameters, measurements from actual survey flights are required. An alternative to these data consists only of the use of the output of a simulation programme of a higher level of sophistication and approximation of the physical reality.

Although the latter has been considered already, it is not realizable in the near future. So the establishment of a model for simulating flight parameters must be based on actual survey flight data. These are available in the photogrammetric community in the form of results of aerial triangulations, in which the camera elements have been recorded and stored.

Actual measurements of flight parameters of survey flights could also be obtained in-flight with the help of special recording equipment, based on gyroscopic and Doppler measurements. So far, these measurements have not been made during survey flights.

A large set of data should be available for the determination of coefficients of the simulation model. The set should be large enough to obtain estimates of the coefficients for different sets of influencing parameters as well as estimates of the variation of the coefficients within a single survey flight. A set could be considered large, if it consists of some tens of camera stations per flight line, and a number of flight lines per block. The camera elements from aerial triangulations should be accompanied by a description of the influencing parameters, as complete as possible, according to table 2.

TENTATIVE QUESTIONNAIRE

No. of exposure stations per flight line			
No. of flight lines			
Type of aircraft			
Flying altitude			
Indicated air speed			
Navigation	Visual	Doppler	Inertial
Compass type			
Flying	Manual	Autopilot	
Autopilot type		"Altitude hold"	Yes No
Proficiency of Crew	Good	Medium	Inexperienced
Frequency of drift measurements			
Drift changes on one flight line			
Mean wind vector			
Frequency of turbulences			
Turbulences	Strong	Medium	Weak
Up and down drafts	Strong	Medium	Weak
Cloud types			
Weather maps	Surface weather	Constant pressure chart	
Max. terrain relief difference			
Maps available		Scale	
Recognition of terrain	Good	Medium	Weak

Table 2. Questionnaire for description of influencing factors of flight parameters.

It is therefore advisable to contact various photogrammetric centres with a request to make available the camera elements as obtained after aerial triangulation. Preferably, these data should, if possible, be the ones after strip or block adjustment rather than before, to eliminate the photogrammetric errors propagated into the camera elements. In addition, the request should extend on to descriptions of factors influencing the survey flights.

In order to allow for selection of the most suitable data, with a spread over a large range of different influencing parameters, it is proposed to organize the contact with photogrammetric centres in two steps: firstly, collection of a list of available material; secondly, selection of that part of the available material most suitable for the present purpose.

6. PLAN OF OPERATION

The block diagram of figure 4 contains the tasks to be carried out and their interrelations for the establishment of a model of flight parameters or camera elements. The project consists of the following number of basic tasks occurring at various places in the sequential process:

Task 1:	Identification and acquisition of actual measurements.
Task 2:	Programming routine for graphically plotting a flight parameter given as a set of discrete values.
Task 3:	Programming a routine for computing and plotting histograms of discretely given function values.
Task 4:	Programming a routine for computing first differences of discretely given flight parameters, for various intervals of the independent variable.
Task 5:	Programming a routine for computation of autocorrelation of a discretely given function.
Task 6:	Programming of simulation model to be used.
Task 7:	Selection of coefficients in simulation model.
Task 8:	Comparison of actual and simulated flight parameters on the basis of histograms, autocorrelation and visual inspection of function plots.

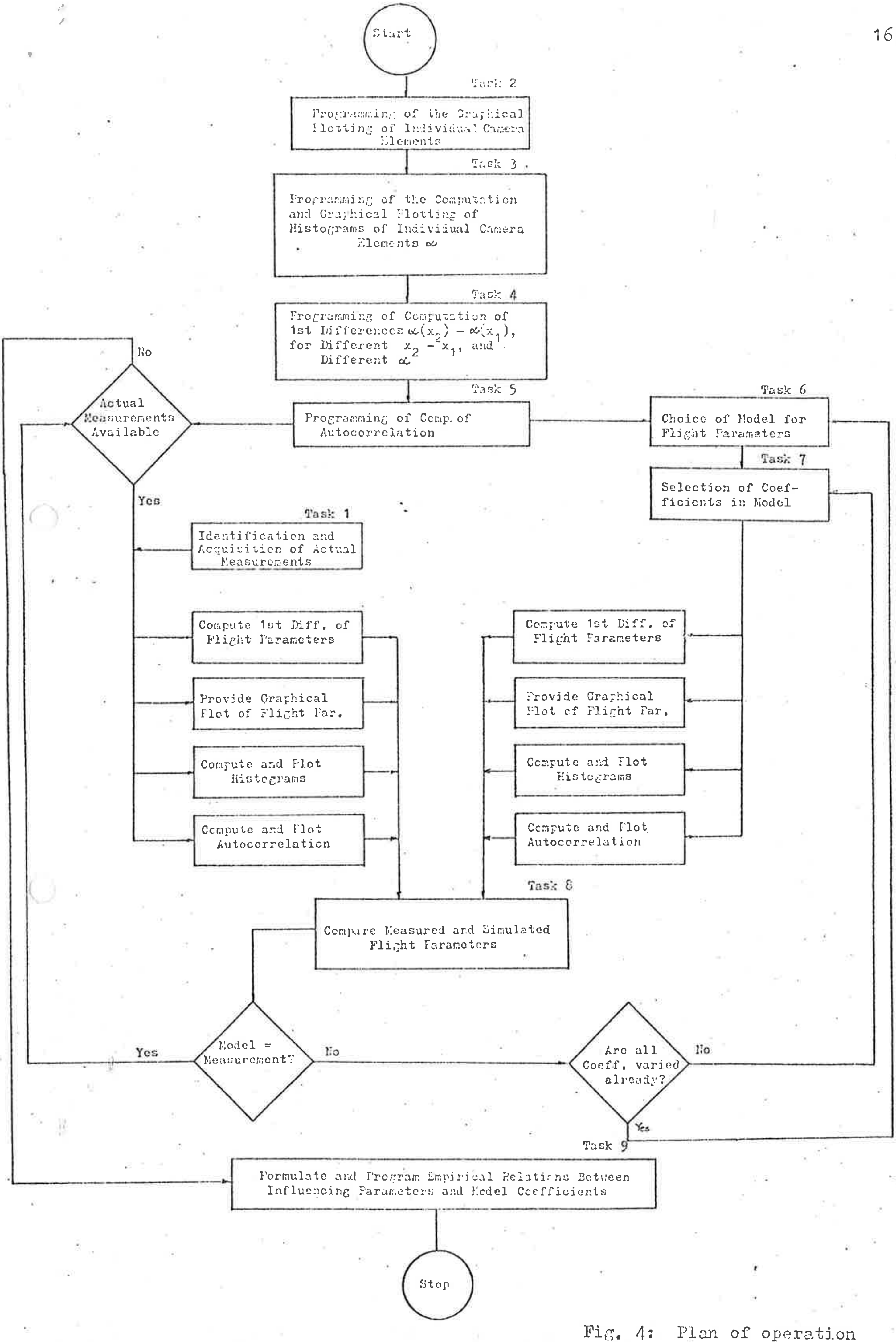


Fig. 4: Plan of operation

Task 9: Establishment and programming of relations between coefficients of model and factors influencing camera elements.

These tasks are partly carried out within an iterative optimization process to find parameters of the simulation model. After an initial phase, in which computer programs are prepared for the required data handling and analysis, and after acquisition of measurements of actual flight parameters, the model for simulating these parameters is experimentally optimized. The model coefficients are varied logically, and the resulting simulated data are analysed. On the basis of this analysis it is decided whether or not the optimum coefficients were obtained. This procedure is repeated per given set of measurements. Empirically relations can then be established between the optimum coefficients and the influencing factors typical for the corresponding measurements.

The computer programming efforts can be kept very small due to the fact that the data analysis in the present project is largely identical to the one required for the simulation of terrain relief. For the latter, programs have already been provided. Also the essential module for the simulation program of flight parameters is already available, as demonstrated in section 3.4. Consequently, the acquisition of actual measurements is a matter of prominent significance for the progress of the project.