APPLICATIONS
OF NAVIGATION SYSTEMS AND OF SENSOR ORIENTATION SYSTEMS IN SURVEY NAVIGATION, IN AERIAL TRIANGULATION AND IN ESTABLISHMENT OF CONTROL.

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ABSTRACT

The application and the economy (i.e. benefit/cost ratio) of using the in-flight orientation elements of the sensor (e.g. camera) are considered.
In navigation it is possible to obtain perfect coverage under all circumstances.
It is reasonable to expect that - in the very near future - part of the costly and time consuming establishment of ground control can be replaced by control obtained by completely airborne instrumentation.

1. INTRODUCTION

From the early beginnings of survey flight use has been made of flight instruments and navigation instruments: barometer, altimeter, air speed indicator, magnetic compass, gyrocompass, solar compass, visual drift sight, visual side sight, etcetera.

In addition to this, several attempts have been made to determine some of the elements of exterior orientation of the aerial camera at the instant of exposure - "auxiliary data" in aerial triangulation:
statoscope, horizon camera, solar periscope, vertical gyroscope, etcetera.

Since several decades modern and highly sophisticated navigation and orientation methods have been developed by virtue of micro-electronics, computerization, nuclear physics, and satellite technology.

Aerial survey has never asked for this progess: modern methods and instruments have been developed, stimulated and budgeted by transport aviation, by military needs and by space programs.

However, once these instruments are available off-the-shelf and once some of them have reached a remarkably high level of accuracy and of reliability, aerial survey cannot afford any more leaving them on the shelf without analysing how exactly they can be put to economical use: how they can be incorporated in survey systems to increase the efficiency and/or the speed of primary data acquisition, and/or to establish control.

It is the purpose of this review to indicate for which purposes these methods and instruments may be put to economical use in two areas of survey: in aerial photography navigation and in determination of the sensor's orientation elements at the instant of exposure.

- In navigation to increase the speed, the economy and the quality of aerial photography.
- In sensor orientation recording: either to economise on time and effort needed to establish ground control, or to make surveying possible at all - in cases where control is be deficient or even is not available - establishing control by purely airborne means.

2. APPLICATIONS

2.1 SURVEY FLIGHT AND NAVIGATION.

2.1.1 General

The two most difficult aspects of photographic flights are

(a) to predict visibility in the area which shall be photographed, and
(b) to navigate the survey aircraft to produce parallel tracks and - preferably - symphotblocks or pin-pointed photography.

In many cases, the navigation (b) is by far the most difficult task, resulting - in micro-economy - in rejection of photography, abortion of missions, and in re-flight of runs in distant mission areas, and - in macro-economy - in non-completion of the season's task and the country's management and development. Aerial photography calls for a navigational performance which is very much higher than the requirements to which flight and navigation instruments are produced, and very much higher than the requirements to which pilots and navigators are trained.

Today's technology has made available excellent navigation instrumentation which can guarantee perfect results under all circumstances - provided they are used by specially trained survey photography navigators, capable to apply the proper methods of in-flight calibration and of periodical updating during flight.

2.1.2 Navigational quality

To produce gapfree coverage (2.1.2.1) we need a minimum performance in lateral (i.e. across flight line) direction; for symphotblocks and pin-pointed photography we also need performance in longitudinal (i.e. along flight line) direction.

For gapfree coverage we need a relative accuracy; for pin-pointing we need absolute accuracy - involving either a ground-based navigation system or a self-contained system (D.R.) combined with updating.
To produce symphotblocks or pin-pointed photography (2.1.2.2), one may use either the 80% or 90% overlap method or a high accuracy electronic system. Sophisticated automatic navigation systems will be used in the medium and larger types of aircraft because of investment reasons; in smaller survey aircraft they will be used when they become available as mass products, lighter and cheaper then they are now.

2.1.2.1 Lateral performance - gapfree coverage
To produce small scale gapfree photography, in many cases the use of Landsat coverage may be adequate.

To produce gapfree photography under constant-drift and zero-turbulence conditions, D.R. methods can be applied, using drift indication, side-sighted updating fixes, and pre-computed turns (calculators, slide rules, graphs). The method fails, however, in cases where instantaneous drift indication is not available, under geostrophic wind conditions, turbulence or mountain wave circumstances, and particularly at large monotonous and featureless areas.

To produce gapfree photography in any scale, these changes of drift are most disturbing sources of errors. In case the Zeiss NA Automatic Navigation Meter would prove tot be operationally reliable also over monotonous terrain, this instrument could give valuable assistance.
Doppler has proven to be an excellent instantaneous drift indicator, justifying its investment even for smaller types of aircraft.
Doppler plus precision compass plus computer is excellent survey navigation instrumentation for all scales - even up to 1: 10.000 - under two conditions:

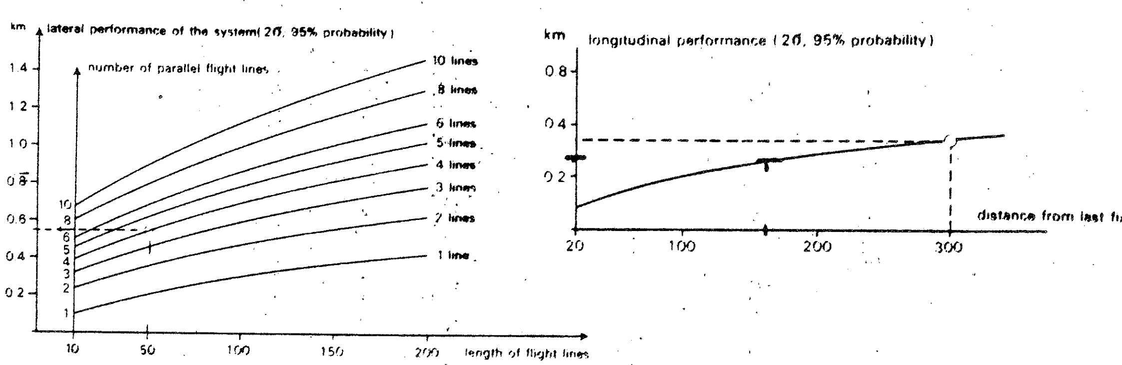
1st. that the complete flight system is properly calibrated in flight [12], and

2nd. that the inherent D.R. propagated error is updated periodically by means of relative updates via navigation telescope or via side sight. [1, 11, 13]

Gapfree blocks of any size can be produced in any scale, taking into account the maximum distance between update fixes. These can be either absolute fixes - i.e. known in coordinates - or relative fixes such as side-sighted track points.

2.1.2.2 Longitudinal performance - symphotblocks and pin-pointed photography
The 80% or 90% overlap method for the "one sheet = one photo" pin-pointing of large scale photography looks attractive in that it saves investment in automated systems; however, it is expensive in that it may produce several thousends of photographes more than needed, and in that it is subject to the camera's cycling time limitation.

The update density of pin-pointing by means of Doppler can be pre-calculated [11,13]:



MAXIMUM DISTANCE BETWEEN DOPPLER UPDATES.

Example: A block of 4 lines 50 km long will accumulate ± 550 km 2σ side lap error; when allowing 10% leeway, strip width can be 5.50 km, being photo scale 1: 25.000 gapfree.

Before end of 4th line, an update must be side-sighted.
These 4 lines (incl. turns ≈ 300 km) will accumulate longitudinal 2σ error ≈ ± 350 m. Pin-pointing to ± 5% overlap shall be within ± 280 m.
A longitudinal updating fix must be taken before 170 km, i.e. after every 2 lines.

A good pin-pointing navigation system is the ground-based microwave beacon system coupled onto CPNS; from the logistics - i.e. operational cost - point of view, this may be limited only to certain specific areas (e.g. France, Germany) where periodical large scale photomap revision is needed. [16, 17, 18, 19]

2.1.3 Choice of survey aircraft and crew composition

A new generation of small "general aviation" craft is being developed: low power, relatively long range, two-seat, light (carbon fibre, fibreglass, etc.) aircraft of revolutionary design.
This new trend may be of importance for aerial survey.
Attempts are made to integrate this lightweight aircraft type with an electronic automated navigation system and with the aerial camera.
This may lead to the minimum crew of two or even one only. It is beyond doubt that high technology (in micro-electronics, aviation construction, etc.) will make this possible. Whether and in which cases this is economically justified depends on a number of other factors: experience of the crew, distance of survey area from base airport, necessity to carry observers, regulation to fly dual pilots, ergonomics overloading of crew, etcetera.

2.2 AERIAL TRIANGULATION

2.2.1 General

Conventionally, aerotriangulation is based on ground control. Establisment of control may account for half (or even more) of the total mapping effort and time, particularly in difficult or inaccessible areas.

In many survey projects, some "auxiliary data" - recorded during flight - have been used to reduce the density of control by means of horizon camera, statoscope, solar periscope, vertical gyro and other instruments.

Today, it is possible to measure and to record all elements of exterior orientation at the instant of photography allbeit in various degrees of performance.

We now have available three groups of data
a. the camera's inner orientation data and image coordinates of terrain features (x, y and principal distance)
b. the camera's (or other sensor's) exterior orientation data (X, Y, Z, dZ, ϕ, ω, κ).
c. the terrain features' ground coordinates (X, Y, Z).

Conventional aerotriangulation uses (a) and (c). Modern instrumentation measures and records (b): This new possibility can be used in various ways, from the simplest use as auxiliary data together with complete ground control, to the other extreme: the use as exterior orientation elements instead of establisment of ground control altogether.

2.2.2 Application of sensor orientation elements as auxiliary data or as constraints to error propagation

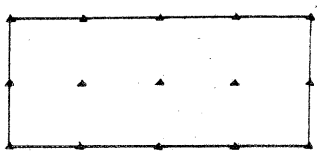
Once the sensor's six exterior orientation elements (X, Y, Z, ϕ, ω, κ) can be recorded and used as such, it is not appropriate any more to call them "auxiliary" data. We propose that such denomination be reserved for the differentials, e.g. dZ, or profiles (statoscope, APR, etcetera).

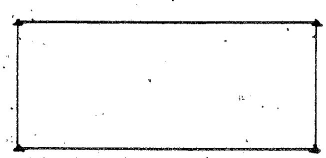
The statoscope has proven to be most useful and extremely efficient. [20, 26] Its basic accuracy - at 3000...6000 m flight altitude - is better than 1 m. After block adjustment, height accuracy is $\sigma = \pm 0.4...0.8$ m, being good for mapping 1:10.000 to 1:5.000. Until now, it is the flight instrument with the highest benefit/cost ratio, capable of saving 60 - 80% of the vertical control.

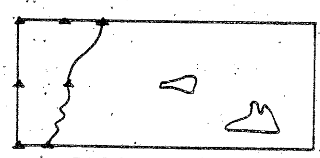
APR (radar and laser) - after adjustment - produces results which are of the same order of accuracy. It is assumed that such accuracy is obtained mainly by the statoscopic component of APR. [21, 23, 24]

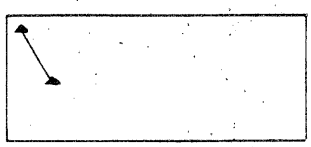
2.2.3 Aerotriangulation with sensor orientation data together with ground control - complete or incomplete. Aerotriangulation without ground control.

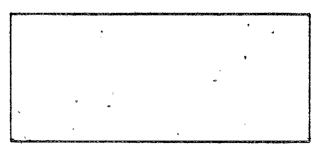
It is reasonable to expect that the use of sensor orientation data - whatever may be available - in combination with ground control data - whatever may be available - will be the most important and the most efficient use of in-flight data in future. This use includes the case that no ground control is available at all. Combined use of aerial and of ground data in one adjustment procedure does have great potential and may solve problems in ground control determination which were virtually unsurmountable until now.


COMPLETE CONTROL


MINIMUM (4 corner) CONTROL


PARTIAL CONTROL


SCALE AND AZIMUTH


NO CONTROL

Various cases can be considered:
(1) Some control is available but is incomplete.
(2) Standard ground control is not available but 3 or 4 ground beacons can be placed at known coordinates.
(3) No control is available, leading to completely self-contained, purely airborne photogrammetry.

. Programs.
To handle cases (1) and (3), programs such as the Simultaneous Multiple Station Analytical Triangulation (MUSAT)[46], the General Integrated Analytical Triangulation (GIANT)[45] and other programs [53, presented at this congress] have been developed.
They incorporate
. image plate coordinates
. ground control parameters, and
. camera station parameters (i.e. the in-flight exterior orientation elements),
which all can be applied with their proper weight factors.

The programs permit a rigourous application of least squares.

For the handling of case (2), see [18, presented at this congress] and [50]: PAT-M-43 has adjusted camera stations' planimetry (X, Y) and differential altitudes (dZ) with the image coordinates - for large scale orthophoto mapping - without ground control.

- Remarks to aerotriangulation without ground control.
  1. The "control points" produced by this procedure are, of course, not monumented but are defined by their image in the photograph.
  2. The sensor orientation data as recorded in flight are not idential to the elements of the camera's absolute orientation as obtained by the photogrammetric procedure. During photography, inner orientation and image point coordinates are distorted (film deformations, atmospheric refraction, etc.); the resulting misfits are minimized by the photogrammetric procedure.
     Consequently, sensor orientation data can be used as absolute orientation elements only in first approximation.

- Result.
  The quality (i.e. accuracy) of the outcome of aerotriangulation depends, of course, on the quality of the input: image coordinates, ground control parameters, and camera station orientation elements.
  Recent investigations [52, 53, presented at this congress] indicate that substantial saving in ground control is obtained when the camera station elements are known to approximately 2 m. (one σ). This can be obtained only by either using ground stations [18, presented at this congress] or completely airborne by hybrids such as GPS/INS. [42]

  The use of Trident III microwave beacons through CPNS has resulted in $\sigma \approx \pm \frac{1}{2}$ m in 1:15.000 photoscale, 1:5.000 map scale. [16, 17, 18, 19].
  The use of a land-based prototype GPS/INS hybrid - without using other ground control - has resulted in coordinate accuracies around the 5 m level; it is anticipated that exposure station coordinates will be determined with $\sigma \approx \pm$ 1...2 m [53, presented at this congress)]

- Potential.
  Application of this new procedure may have a tremendous potential in future.
  Examples:
  - mapping of isolated areas, of thousends of lakes (in-shore) and airborne bathymetry of continental shelf (off-shore)
  - reefs, river deltas, swamps and multiple-island areas;
  - mapping and inventory of near-inaccessible tropical forests and mountain areas;
  - topographic mapping or DTM mapping from orbiter or spacecraft.

2.3 USE AS POSITIONING FOR OTHER SENSING DATA.

When the need arises for remote sensing to produce data, one of the major difficulties is to accurately locate the position of the sensed data. Here, the sensor orientation methods come in usefully, in particular planimetry (X, Y) but also altitude (Z).

2.3.1 Examples of applications.

- To provide quick semi-controlled photo map sheets, for planning purposes. Aerial photography, synchronized with the recording of position coordinates and of vertical laser height may have a high macro-economical value in providing photomap sheets for planning, within one day's time.

- Bathymetry to 30 cm performance, ($\sigma \approx \pm$ 15 cm) - providing off-shore data of the continental shelf or in-shore data of lake depth to 3 Secchi - needs positioning, either approximately (off-shore) or accurately (in-shore) to a performance of about 2 m. [55][56][57]
- Forest mapping. The narrow laser beam - in addition to recording profiles of the tree canopy - can penetrate up to 99% canopy and 1% transparancy in tropical and subtropical forest. This is done in combination with INS position recording. [58][59].

  In geophystics sensing - magnetometry, radiometry, etcetera, the positioning is the major problem as well. The use of self-contained methods (INS, Doppler, GPS/INS etc.) plus recording is a "must" for post-flight processing.

3. ASPECTS OF ECONOMY.

- Cost - investment and operating cost, can be calculated
- Benefit - can be quantified as well
- "Economy" = benefit/cost

3.1 COST

Investment in simple visual type navigation equipment is negligeable.
Investment in modern technology may seem high in absolute sense but in relative sense it is very moderate. Example: Doppler in turboprop aircraft and GPS/INS in jet aircraft may require no more than 5 - 10% of total survey flight system ready-to-operate.

Operating cost of the visual and turn-precomputing instruments is negligeable.
Doppler, GPS/Navstar and avionics maintenance cost is low.
INS maintenance will now be near the 10% per year bracket; it is expected to be reduced significantly with the advent of the strap-down and leaser-gyro generation.

3.2 BENEFIT

- Benefit in navigation.

  In every survey Organization statistical evidence is avialable about the total cost of navigation-abortive photo flights.
  The proper choice of navigation instrumentation and of navigation methods can guarantee gapfree coverage and pin-pointed photography for orthophotomapping, avoiding re-flights completely. Thereby, the benefit in navigation is quantified.

- Benefit in saving ground control.

  From the very beginning of aerial survey until today, establisment of ground control has been one of the heaviest budget items. In nearly all cases of difficult terrain (mountainous, tropical forest, swampy areas, sand desert, permafrost, etcetera) it is the heaviest item, not only in cost but - most awkwardly - in terms of time and delay of production.

3.3 ECONOMY

Economy - per definition - is measurable in terms of benefit/cost ratio.
The cost as well as the benefit can be quantified in terms of micro-economy and/or in terms of macro-economy. Micro-economy refers to the direct cost and the direct benefit of the simple product, - e.g. acquisition cost and price of the aerial photograph, as is often done in contracting for aerial photography. Macro-economy refers to total cost and total benefit of the final product, e.g. execution of a 5-year plan, planning and execution of infrastructure

(harbours, power lines, communication and transportation), development plans, management of the country.

Note: Very often in macro-economy, the factor "speed (time)" has a much higher weight than the factor "direct cost".

When calculating the benefit/cost ratio in micro- and macro-economical sense it becomes obvious that the use of existing modern high technology instrumentation can bring about an enormous gain in economy.
In the majority of cases there will be no justification any more for not making use of the possibilities which are offered to aerial survey today.

4. CONCLUSIONS

4.1 NAVIGATION

The state of the art is such that perfect navigational coverage can be obtained at all photo scales, under all circumstances (constant instantaneous drift indication, INS, Doppler plus computer, microwave beacons, CPNS e.o.) - including pin-pointing.

4.2 AEROTRIANGULATION (A.T.)

- The economy of A.T. based on complete control can be improved significantly by applying statoscope.
- Economy and accuracy of A.T. based on minimum (i.e. 4 corner) control can be improved significantly by using statoscope plus planimetric coordinates of the camera stations in flight.
- A.T. based on incomplete ground control and even on no ground control at all is possible when GPS/INS hybrid is available together with a monitor station. Already today, small scale mapping without ground control is feasible. It is reasonable to expect that in the very near future medium scale mapping without ground control is a realistic possibility for routine production.

4.3 PROGRAMS

For A.T. using all in-flight orientation elements of the sensor (camera), the MUSAT and the GIANT programs are available.

Some other programs do not use the attitude [50, 53].

It would be advisable to integrate the application of dZ into GIANT.

4.4 INSTRUMENTATION

It is reasonable to expect that aerial survey will be revolutionised by lifting the problems of establishing control from the ground to the air.

To this end, most useful instrumentation may prove to be:- microwave beacon systems
- GPS/INS hybrids, in combination with one ground monitor.

4.5 ECONOMY

- It is possible to produce perfect survey navigation results - under all circumstances.
- It is possible to replace establishment of ground control by the use of exterior orientation elements determined in flight.
- The economy (benefit/cost ratio) of these possibilities is such that the use of navigational high technology should be considered seriously.
- This consideration is valid in micro-economy; it is the more valid in macro-economy.

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