

H I G H   A C C U R A C Y   X , Y , Z   P O S I T I O N I N G  
I N   F L I G H T

François L. J. H. CORTEN  
Emeritus Professor, ITC  
Consultant,  
Aerial Photography, Survey Flight and Navigation  
THE NETHERLANDS

Commission I, ISPRS  
Kyoto, Japan, 1988

Prof. Ir F. L. J. H. Corten  
Vuchtelanden 12, 7542 MD ENSCHEDE, Tel. 053/770579. Tx 72160 helm nl  
THE NETHERLANDS

**ABSTRACT**

A new Computer Controlled Navigation System ( CCNS ) is described which upgrades the performance of existing navigation facilities and instruments to a higher level of accuracy than that for which these facilities were originally designed.

Also, CCNS is described:

1. as an automated precision navigation system,
2. as a system to record the aircraft and camera positions and altitudes in flight - in a highly accurate way, in terms of meters and fractions of meters as against miles and fractions of miles,
3. as an automated flight management system,
4. as a system to produce data for aerial triangulation, thereby replacing the cost and time consuming establishment of ground control by fast and efficient in-flight aerocontrol,
5. as a tool for precision calibration of aviation facilities and airways,
6. as a possibility to complement satellite remote sensing data to complete geographic information systems by integrating airborne data with remote sensing data.

The possibility to have a highly accurate record of the X,Y,Z positions of all data produced during flight is a performance which has never been produced before; high technology has made this possible today.

In aerial survey, this leads to a level of accuracy of aerocontrol which is sufficient to be used as control for medium and large scale mapping. This use of aerocontrol in combined adjustment to replace establishment of ground control is announced as a new approach in aerial survey which will have an enormous impact on mapping.

In other fields of aviation, the recording of the aircraft's high accuracy in-flight position and altitude - in fractions of meters accuracy - is a new approach which will lead to various new applications.

## CONTENTS

1. Introduction
2. Instruments
3. Performance
4. Applications
5. Aspects of economy
6. Conclusions
7. Reference literature

### 1. INTRODUCTION

From the early days of aerial photography - using primitive WW I aeroplanes - until today's space age, precision navigation and accurate positioning have been the major problems in survey photography as well as in many other applications of aviation.

As a matter of fact, the problems of "precision navigation" - i.e. guiding the airplane precisely along a predetermined path over uncultivated or over large and featureless areas - and the problems of "accurate positioning" - i.e. obtaining a record of each camera station in flight, in terms of meters or fractions of meters instead of miles or fractions of miles - have not yet been solved.

In aerial survey and photogrammetry, the orientation of the aerial photographs has always been the fundamental problem. Until recently, the orientation problems in photogrammetry were based on indirect determination of the camera orientation elements by means of aerial triangulation using ground control points.

Modern technology, however, has made it possible for survey to determine the camera orientation elements at the instant of exposure directly, at a degree of accuracy which is acceptable for not only small and medium scale mapping but even for large scale mapping.

The solution of this fundamental problem in aerial survey is made possible by three facts:

1. A Computer Controlled Navigation System (CCNS) is available, capable of calibrating existing navigation networks and instruments - such as DME/TACAN, Loran-C, GPS and other navigation facilities - to a level of performance higher than that for which these facilities were originally designed,
2. the Computer Controlled Navigation System is capable of determining X,Y,Z position and altitude with extremely high accuracy at the instant of exposure,
3. New methods of combined adjustment make it possible to use these high accuracy in-flight positioning data as a means of replacing the cost and time consuming establishment of ground control by the use of "aerocontrol".

In aviation - and, in general, in all airborne activities, civil and military - this highest accuracy in-flight recording will lead to a variety of new applications.

Aerial photography has been under development since more than a century. Still, it seems, most people - even surveyors - do not realize that flying for aerial survey calls for a very much higher navigational precision and positional accuracy than any other application of general aviation. Consequently, no commercially available navigation system or

facility whatsoever will be acceptable for guidance and management of survey missions - be it GPS or any other method or instrument - unless incorporated with CCNS.

In addition - as long as the GPS network is not yet completed - GPS may be hooked onto existing CCNS equipment at any time desired - now or at a later stage.

## 2. INSTRUMENTS

### 2.1 Basic set-up

The Computer Controlled Navigation System **accepts input** - the flight plan, data from navigation facilities and instruments, data from sensors such as aerial photography and airborne remote sensing.

It **upgrades the performance** of some of these facilities to a higher level of accuracy than that for which these facilities were originally designed.

It **maintains the communication** with the pilot, the users of aerial photography, users of coordinates and positions and with the autopilot.

It **produces various types of output in a user-friendly way** - automated precision navigation, high accuracy records of all positions, data for aerial triangulation, aerocontrol to replace ground control, management of the mission, administration, flight plot and other types of output as desired by the user.

### 2.2 Configuration

The configuration is presented in diagram figure 1.

## 3. PERFORMANCES

The performance of CCNS depends - at the one side - on the navigation facilities used as input and - at the other side - on the way of processing the output.

The figures mentioned in this treatise assume that no additional errors are introduced in the checking phase - i.e. ground control and maps to check the positional error of the flight line.

In aerial survey, in general, the results of the navigation precision are of interest directly - during flight, on-line, before or without subsequent photogrammetric adjustment.

This precision of navigation can be said to be of the order of 150...10 m (one sigma) when LORAN-C is used as input.

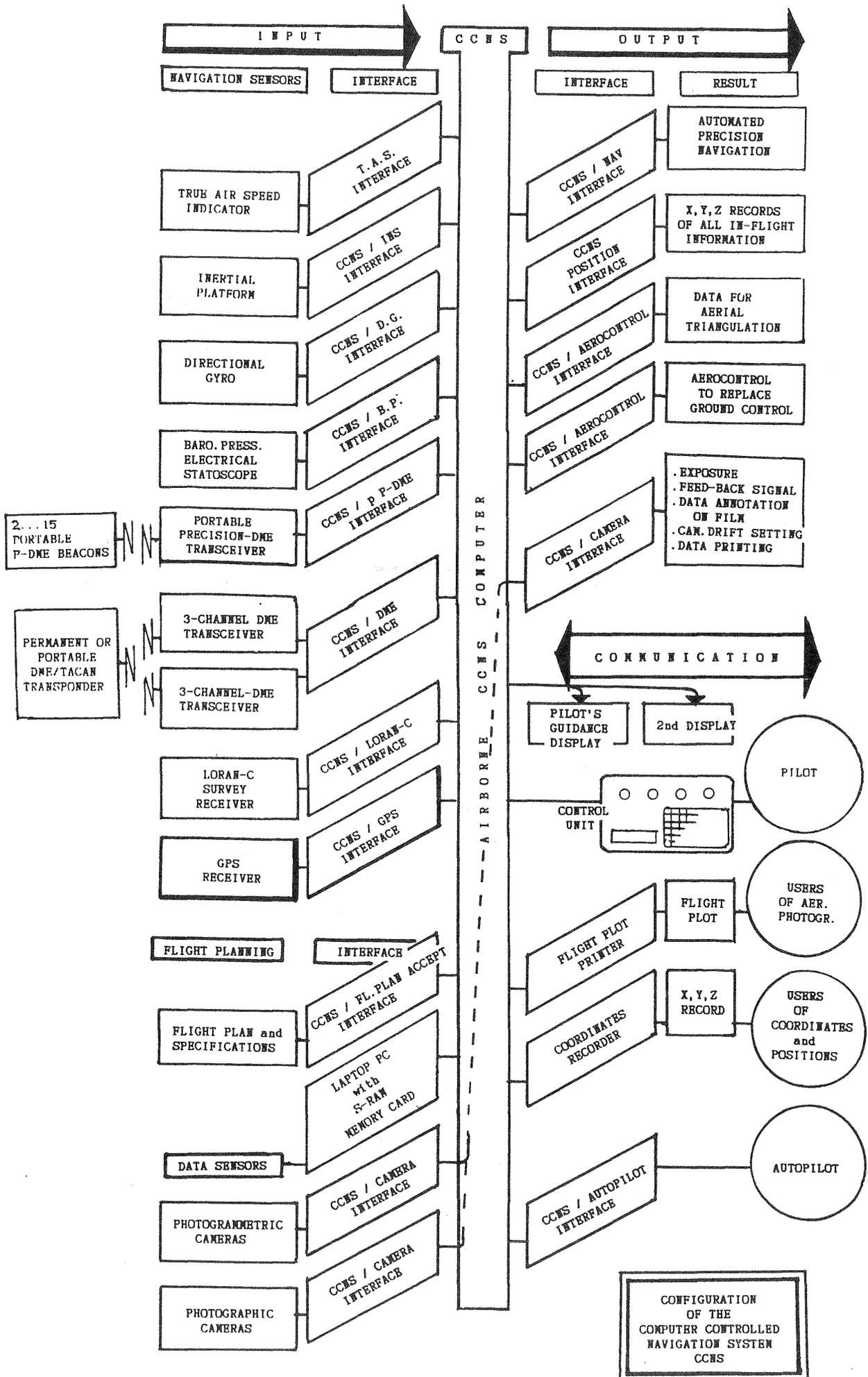
It will be of the order of 15 ...5 m when the navigation is based on a DME-TACAN network - depending on the number of beacons, on their distances and on the configuration of the network.

It may be of the order of 5...3 m when based on precision-DME beacons.

It is expected to be of the same order of precision when based on GPS - after full deployment.

Such navigational precision has never been reached before and may safely be called "perfect" for even the largest photo scales.

The highest positional accuracy - in general - will be of interest to users in the mapping and in the survey branch. They will record the "aerocontrol" - the position of the photogrammetric camera at each instant of exposure. The corresponding photographic coverage will be adjusted in combined block adjustment - after flight, off-line. This will result in a positional accuracy of all image points in the order of 5...0.5 m (one sigma).



It will be of the order of 2 m or less when based on more than two precision-DME beacons and is expected to be of the same order when based on GPS - after full deployment.

Such positional accuracy has demonstrated to be good enough to lead to triangulation for medium end even for large scale mapping. Also, it has been demonstrated that it can always fully replace terrestrial ground control with regard to the accuracy of the block triangulation: ground control points are required merely for the datum transfer - i.e. in order to establish the relation to the geodetic coordinate system. This highest positional accuracy is of basic importance for **aerial survey** and **ground survey** not only but also for **satellite remote sensing** and its use in **geographic information systems** - i.e. for integrating detailed airborne data with global satellite remote sensing data. This is made possible because the positional accuracy of CCNS can be made higher than that of the smallest pixel dimensions.

Finally - **in aviation** - the position and movement of any aircraft in flight is recorded with an accuracy which is an order of magnitude higher than that which was possible until today. The impact of these new performances on aviation and on engineering is expected to be as heavy as the impact on remote sensing and on geographic information systems.

#### **4. APPLICATIONS**

##### **4.1**

##### **General**

The impact on various fields of aviation is expected to be considerable. Some of the most obvious examples are mentioned below.

##### **4.2**

##### **Aerial photography and aerial survey.**

##### **Precision navigation and**

##### **high accuracy position recording**

1. In aerial photography, precision navigation has always been one of the most difficult problems of the profession. Today, however, it is possible to produce "perfect" navigation as well as high accuracy position recording in flight.

The navigation for aerial photography and remote sensing may be managed and carried out by CCNS with the precision of approximately 15 m (one sigma) or better - during flight, on-line, without adjustment.

The position recording may be carried out in the order of accuracy of 3 m or better - off-line, after flight and photogrammetric adjustment.

Aerial photographs and airborne remote sensing data are positioned at precisely predetermined locations, with an accuracy in the order of 15 m per photograph.

2. Aerial photography and remote sensing are powerful tools for recording the "what?" - the qualities - of objects. Neither of them, however, is capable of recording the "where, exactly?" - the exact location of these objects.

CCNS has made it possible to record the exact position of any observation made during flight - at highest accuracy - and this new high-tech possibility is expected to lead to many new applications.

3. Output: Coordinate systems.

The flight plan, the automated precision navigation, the high accuracy X,Y,Z position records and coordinates, the flight plot, the data for

aerial triangulation, the aerocontrol, etcetera, may be produced in any coordinate system desired.

4. Survey missions had to be managed, navigated and administered by the survey flight manager - according to the flight plan and to the ambient conditions. Today, the guidance as well as the administration and the complete management may be automated by the Computer Controlled Navigation System (CCNS). The flight plan, for instance, may be absorbed, the management and the mission administration conducted and the flight plot produced automatically, immediately after landing.

5. Professional survey pilots, navigator/photographers and survey flight managers have always been extremely hard to get. Modern technology has made it possible to replace 2 out of 3 of these specialists as well as their heavy navigation/drift/control sights by automated CCNS managing equipment, at the same time making room for additional fuel and thus allowing for greater survey flight economy.

#### 4.3 Aerocontrol to replace ground control

- A set of ground coordinates is commonly referred to as "ground control".

- A set of coordinates determined from a photogrammetric image, in combination with the camera's known inner orientation elements, is commonly referred to as "plate coordinates" or "image coordinates".

- This author introduces the concept "aerocontrol" to indicate a set of camera orientation elements  $(X, Y, Z \text{ or } \Delta Z, \phi, \omega, \kappa)$  - either all or part of these - which are determined at the instant of exposure.

Aerocontrol is used in combined adjustment together with the plate coordinates and with or without ground control. It does not consist of terrain points which can be monumented but of the aerial camera's exterior orientation elements which are determined during flight.

Aerocontrol is instantaneous. The combined adjustment ( block triangulation ) can be repeated at any time with the same accuracy but without reference to a fixed set of control points. In each repetition, the camera positions at the instants of exposure are determined and used as control.

In conventional topographic mapping, photogrammetric block triangulation is applied as a standard tool: known ground coordinates ("ground control") are used to transform model or plate coordinates - derived from aerial photography - into geodetic coordinates.

The establishment of ground control has a number of serious disadvantages:

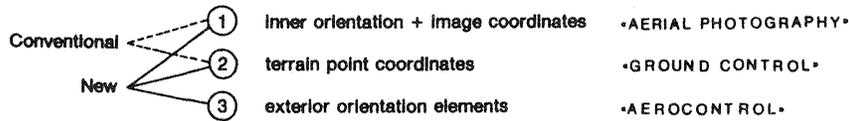
- tremendous cost and tremendous time and effort are needed to establish, monument and signalize ground control,  
- targets and monuments disappear, especially in populated areas.  
For these reasons, it is attractive to move the control from ground level to flight level by means of "aerocontrol".

Obviously, the logistics (i.e. cost and time) of establishing aerocontrol is incomparably easier, faster and cheaper than those of establishing ground control, particularly in areas where access is difficult.

It is anticipated that the conventional methods of block triangulation using aerial photography ("1" in figure 2) and ground control ("2" in figure 2.) will be replaced by the new and more economical methods of

combined point determination using aerial photography ("1"), ground control ("2") and aerocontrol ("3") in a combined block adjustment.

FIGURE 2. Aerial triangulation and adjustment.



#### 4.4

#### Ground survey

Ground survey - the major retarding element in aerial survey - may be replaced by efficient and fast aerocontrol.

#### 4.5

#### Satellite and airborne remote sensing.

#### Geographic information systems

Aerial photography is the most efficient means of producing information - in greatest detail and in geometric integrity - about the Earth's surface.

Satellite remote sensing has developed to a most powerful means of producing global information about the Earth and the environment of its inhabitants.

Computer engineering has developed into a most powerful tool for processing the data which is produced by remote sensing and other means. This development has led to the insight that a geographic information system can be really useful only if information from various sources - satellite remote sensing as well as airborne data acquisition and from terrestrial sources - is integrated and processed to the solution of human-related queries.

Integration of aerial photographic data with satellite remote sensing data shall be performed both on the quality aspects and on the geometric aspects of the data.

Until today, integration has been extremely difficult because the geometric attributes which are needed to relate airborne data to satellite remote sensing data were not available at sufficient accuracy. Integration, therefore, is not done in practice and remote sensing data remain ineffective through lack of detail, of positional accuracy and of geometric integrity.

This situation, however, has changed now because the airborne data produced by CCNS - after photogrammetric adjustment by means of aerocontrol and combined block adjustment - have a positional accuracy better than that of the smallest satellite remote sensing pixels:

...LANDSAT's MultiSpectral Sensor (MSS) has produced pixels of 80 m size;

...its Thematic Mapper (TM) pixels of 35 m;

...SPOT-1 and SPOT-2 both have pixels of 20 m and 10 m;

...The advanced LANDSAT-7 sensor, the stereo-MOMS and the SPOT-3 will have a resolution of 10 m pixels as well.

...SOYUSKARTA's products consist of 5 m pixels.

...CCNS's positional accuracy of the image points is of the order of 15 m - on-line, during flight, before adjustment - and of the order of

3...0,5 m off-line, after flight and after photogrammetric adjustment.

Thus, integration of airborne data with satellite data can be performed directly and this fact will have an enormous impact on production and use of remote sensing not only but - more particularly - on the production of "complete" geographic information systems.

This integration of aerial photography data with remote sensing data to produce more useful geographic information systems is made possible by CCNS because the positional accuracy of the photo image points - after adjustment by means of aerocontrol and combined block adjustment - is higher than that of the smallest pixel dimensions.

#### **4.6**

##### **Civil engineering**

1. Terrain profiling
2. Construction of digital terrain models for civil and military purposes
3. Establishment of height control along APR techniques

#### **4.7**

##### **Aviation**

The impact on aviation and its applications is expected to be as heavy as the impact on remote sensing and on geographic information systems engineering.

The position and movement of any aircraft in flight is recorded at an accuracy which is an order of magnitude higher than that which was possible until today.

This leads to the following applications:

1. Conversion of civil and military aircraft into single crew survey aircraft
2. Calibration of controller's radar, airway beacons and other facilities
3. Recording the positions of moving objects - on land and at sea
4. Search and rescue

The position of any target may be recorded in high accuracy coordinates. This is of vital importance particularly when deteriorating visibility might prevent locating the target at a later stage.

5. Engineering applications of aviation
6. Meteorology research. Air masses
7. Environment and pollution

#### **5. ASPECTS OF ECONOMY**

In this treatise, "Economy" will be defined quantitatively as the value of the ratio: benefit/cost.

##### **Micro-economy and macro-economy**

In micro-economy, one strives for the lowest cost of each individual product - e.g. the aeroplane, the photograph, the computer - irrespective of the country's needs.

Macro-economy refers to the total cost and the total long-term benefit of the final result - e.g. improvement in infrastructure, growth of the country's economy, efficiency of geographic information systems, etcetera.

It may well be that an item's cost is high in micro-economy but that its benefit in macro-economy is very much higher than that cost.

It is obvious that this high degree of economy may be reached particularly when using CCNS in various applications.

## 6. CONCLUSIONS

1. Positioning of aircraft in flight is possible with an accuracy which has never been possible before: This accuracy has demonstrated to be of the order of 3 m (one sigma)...0.5 m ( ! ).

2. That fact allows for navigation - i.e. on-line, during flight - which is "perfect", i.e. of the order of 15 m , acceptable for even the largest photo scales.

3. It also allows for positional records of photo image points - off-line, after flight and after photogrammetric adjustment - which are accurate to the order of 3 m...0.5 m (one sigma).( ! )

4. These new possibilities in high technology will have an impact on surveying and on other fields of engineering which is considerable:

### 4.1. Impact on surveying

---The navigation in aerial photography and remote sensing may be "perfect" at all scales - all observations being located precisely at predetermined positions.

---The management of survey missions may be automated and carried out exactly according to flight plan - producing the administration and flight plot automatically. This automation of management increases the fuel capacity, the productive mission time and the survey flight economy considerably.

Position records of all photo points and of all observations made during flight may be available - to a high degree of accuracy.

---Aerocontrol may be produced on behalf of using it in combined block adjustment and this use of aerocontrol may replace the cost and time consuming establishment of ground control.

---APR surveying leads to a tremendous saving in cost and time in the establishment of height control.

### 4.2. Impact on remote sensing and geographic information systems engineering

---Aerial photography - producing information about the Earth's surface in greatest detail and geometric integrity - may be integrated with remote sensing information, thus producing really useful geographic information systems.

### 4.3. Impact on civil engineering

---Terrain profiling greatly economizes various types of civil and military engineering.

---Digital terrain models provide economy and speed to planning and execution of civil engineering.

### 4.4. Impact on aviation

---Any type of aircraft may be converted into single crew survey aircraft in a simple and cost-effective way - using an external pod for the

photography and the remote sensing and CCNS at the pilot's station for the navigation, the position recording and the flight management.

---Flight control radar, airways, beacons and other facilities may be calibrated to highest precision.

---Position and movement of aircraft during flight may be recorded at fractions of meters accuracy.

---Search and rescue and other target locating activities - at stationary and moving targets, on land and at sea, during daytime and at night - may produce high accuracy records of target positions.

#### **4.5. Impact on meteorology, environmental research and other applications**

---Meteo research on the properties of air masses may be carried out in 3-D.

---Environmental research - such as pollution - on gas masses may be carried out in a similar manner.

#### **5. Various fields of engineering and technique.**

The new high-tech possibilities of precision navigation - by day and at night - and of high accuracy X,Y,Z position recording during flight are expected to have an enormous impact on various fields of engineering.

Once a new technique has been developed, it may be expected to open up new applications of engineering to respond to various technical and human-related queries.



#### **7. REFERENCE LITERATURE**

Ackermann, F., Performance and development of aerial triangulation for mapping, 5th UN Reg. cart. conf. for Adrica, Cairo, 1983

Ackermann, F., Utilization of navigation data for aer. triangulation, IAP, vol. 25-A36, Rio, 1984

Beumelburg, J., Grimm, A., Heimes, F.-J., CPNS, Computer Controlled Photo Navigation System, Proc., workshop CPNS, Hilchenbach, 1983, 5p.

Corten, F.L.J.H., Survey navigation and determination of camera orientation elements, Comm I, ISP, London, Photogrammetria XVI, 251...285, 1960

Corten, F.L.J.H., Navigation systems and sensor orientation systems in aerial survey, Comm. I, ISPRS, RIO, 1984, 80p., 28p.

Friesz, P., The Navstar Global Pos. System for aer. triangul., Instit. f. Photogramm., Univ. Stuttgart, 1987

Schwartz, K.P., New instruments, new methods, future prospects, Proc. 17th FIG Congr., Sofia, 1983

Schwartz, K.P., Fraser, C.S. Gustavson, P.C., Aerotriangulation without ground control, ISPRS, RIO, 14 p. 1984,