C P N S

COMPUTER-CONTROLLED PHOTO NAVIGATION SYSTEM

NEW ASPECTS FOR AERIAL SURVEY

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1. INTRODUCTION

A first paper about CPNS has been presented to the ISPRS-Symposium of commission I, Canberra 1982 /3/, reporting about a concept of computer-controlled navigation for aerial survey and remote sensing. In the meantime in-flight testing of CPNS has been carried out, the system is now ready for service.

2. GENERAL ADVANTAGES

Aerial photographs provide the basic source material for topographic mapping and development planning; but up to now it has been a problem to produce optimum quality aerial photographs exactly at preprogrammed positions /3, 6, 8, 9/.

For environmental studies or environmental monitoring purposes remote sensing is a useful tool. To produce remote sensing imagery at day or night, precise navigation is required and a record of actual flight parameters helps solving geometrical problems /10, 17/.

CPNS can satisfy basic needs which exist in optimizing flight missions for:

- aerial photography
- remote sensing
- maritime patrol/surveillance
- flight and airways inspection
- search and rescue etc.

The following benefits are obtained by CPNS in the field of aerial photography and remote sensing:

+ any good weather chance can be exploited to maximum extent
+ reflights because of navigational problems are not necessary any more
+ night operations for remote sensing flights do not create any extra navigational problems
+ for monitoring purposes aerial photographs or remote sensing imagery can be obtained repeatedly at exactly the same positions
+ piloting can be carried out by non-survey-experienced pilots /2, 18/.

3. SPECIAL ADVANTAGES FOR ORTHOPHOTO-MAPPING

Orthophotos have become a very important mapping product. At present most orthophotos are produced in black and white, nevertheless the production of colour-orthophotos is in strong progress.

For orthophoto mapping and for the subsequent carthography, invaluable savings occur by avoiding the composition of several orthophotos into one map sheet.

"ONE PHOTO = ONE MAP SHEET"

has therefore become a well established principle /6, 16/. For large scale work and/or colour-orthophotos it is not justified or even impossible to produce the photos according to the conventional 80%- or 90%-overlap-method; but pin-pointed aerial photography by means of CPNS is the only realistic solution*).

For areas with existing DME (digital terrain model) data, stereoscopic coverage is not needed at all for orthophotography; only one photo per map sheet is sufficient. This saves 7/8 of photos compared to the conventional 90%-overlap method.

4. SPECIAL ADVANTAGES FOR AEROTRIANGULATION

CPNS produces 'pin-pointed' photography. This saves approximately 1/3 of the number of aerotriangulation transfer points.

CPNS records X-, Y- and delta Z-coordinates of all exposure stations. Introducing this data as auxiliary data into the aerotriangulation adjustment process (e.g. PAT-M-43; Prof. Ackermann, University Stuttgart), the number of ground control points can be reduced drasticly. For medium and small scale projects first investigations by Prof. Ackermann /1, 19/ have shown, that aerotriangulation might be possible without any planimetric ground control point!

5. POSITIONING/DISTANCE MEASURING EQUIPMENT

CPNS is based on digital processing of positioning or slant range data. The accuracy of CPNS depends on the accuracy of the above data.

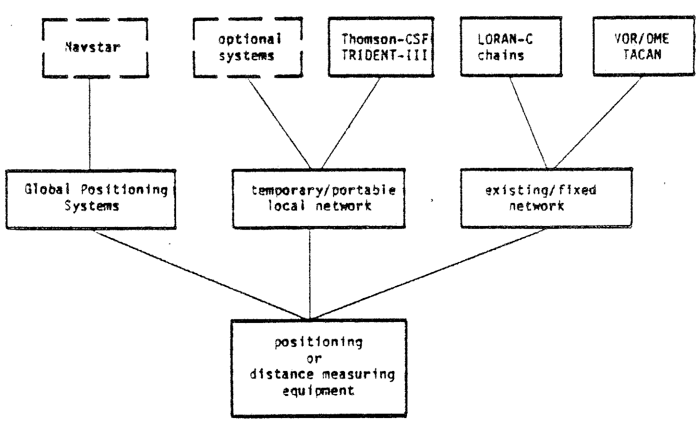


Fig. 1: CPNS based on different positioning/distance measuring equipment

5.1 CPNS in Areas with Existing/Fixed Network

The accuracy requirement for aircraft positioning should be in the order of +/- 50 meters. This accuracy can normally not be obtained from existing Loran C or VOR/DME, TACAN equipment. Only by applying in-flight calibration procedures and interpolation techniques according to geodetic least square adjustment principles, this accuracy can be obtained

*) Mr. Brunnthaler, President of HANSA LUFTBILD at the Photogrammetric Week, Stuttgart 1983 /6/: If the required photo scale is a large one, the cost of the film material for 80 or 90 % overlap is high as compared to the operating cost of the aircraft. Besides, on large photo scales, the cycling time of the camera between exposures will not allow 80 or 90 % overlap. One has to use pin point photography, otherwise an assembly of orthophotos or parts of it to cover a map sheet cannot be avoided.

in absolute sense. This accuracy is sufficient for optimizing the navigational result of survey flights. The big advantage of this method is, that large areas of the world are covered by existing network.

5.2 CPNS in Areas with Temporary/Portable Local Network

In areas without existing networks for aviation or maritime use, a local network can be established. Very accurate, portable equipment, like the Thomson-CSF TRIDENT-III, is existing. Depending of flight altitude an area of 150 x 150 Km^2 can be covered by four ground beacons. For larger areas or even whole countries, networks up to 32 differently coded beacons can be established.

The accuracy of aircraft positioning with the TRIDENT-III is in the order of +/- 2,5 meters. This accuracy not only allows to optimize the navigational result but can produce auxiliary data for aerotriangulation to reduce planimetric ground control as well /1, 4, 5, 19/.

6. CPNS BASIC SYSTEM

The basic concept of CPNS is illustrated in figure 2. The CPNS computer calculates from positioning or slant range data guidance information according to the flight planning parameters. This information is presented on a graphic guidance display. The pilot/navigator communicates with the CPNS computer by means of the control unit (hand-held-terminal). Only a few functions are necessary to operate

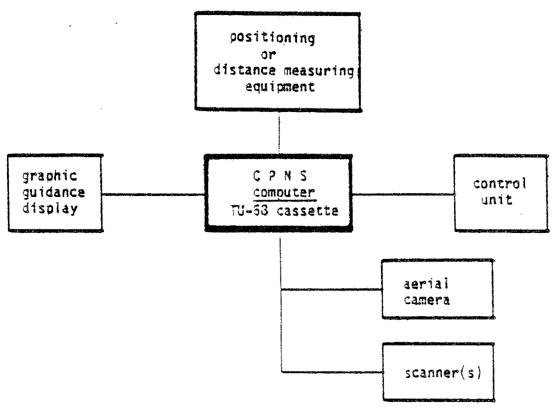


Fig. 2: CPNS basic system

the userfriendly system. Experiences have shown, that a pilot can operate the system and fly accurately according to the display after a short introduction /2/. Pin-pointed photography is produced by firing the aerial camera via the computer. Interfaces for WILD RC-10 and RC-10A as well as for C.ZEISS RMK's and the JENOPTIC LMK aerial camera have been prepared. Flight data (X, Y, delta Z) are recorded on cassette.

7. CPNS BASIC FUNCTIONS

7.1 Computer Supported Mission Planning

By means of the CPNS computer and the control unit mission planning can be carried out. Reference lines are defined (coordinates of starting points and end points, or coordinates of starting points plus line directions and line lengths). Flight altitude and distance between photos (air base) are requested from the computer for each reference line. Each reference line may have a number of parallel lines (with the same mission parameters as the reference line); i.e. for a block-shaped mission with constant line spacing and constant flight altitude only one reference line is to be defined, parallel lines may be left or right from the reference line.

7.2 Pilot's Guidance on the Graphic Guidance Display

Efficient guidance information is presented to the pilot in graphical form on a screen. Figure 3 demonstrates the basic display. The principle "follow the needle" (aircraft fixed, ground moving) - well known to pilots - has been chosen.

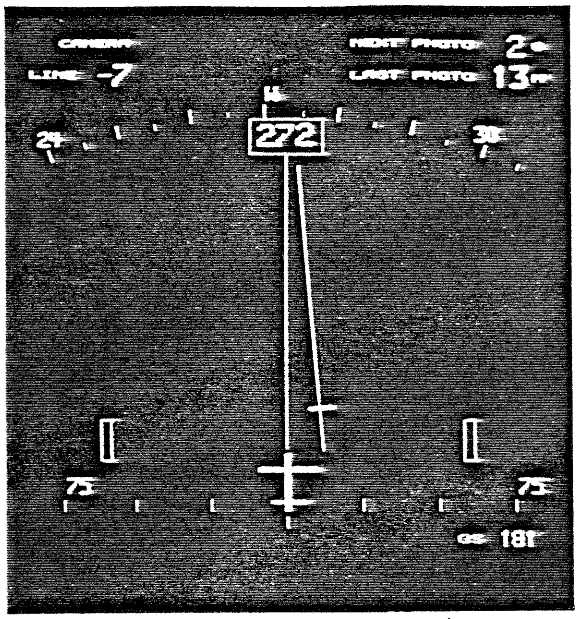


Fig. 3: Example of 'graphic guidance display'

Information at the top: Camera is in stand-by mode, line number -7 has been selected, next photo will come after 2 seconds and the last photo of line no. -7 is obtained after 13 minutes. Other information: The aircraft is flying a true track of 272 deg. The lateral deviation from the planned survey line is about 20 m to the left, aircraft is correcting to the right.

After a line number has been introduced into the CPNS computer by the control unit, it is easy to intercept the selected line. The line number may be selected far before reaching the line. The desired track line only appears in case the interception angle is less than 35 degree; otherwise a small square symbol appears at the lower horizontal line. This symbol indicates the lateral deviation from the selected line. The scale for lateral deviation changes automatically, the largest corresponding to 75 meters, then 150 m, then 300 m, 600 m, 1.2 Km, 2.4 Km, etc. up to 77 Km maximum lateral deviation. Line interception may be carried out from any of the two directions. Line nimber is correspondingly introduced with 'plus' or 'minus' sign into the computer.

7.3 Commanding the Camera, Computing and Recording X-/Y-coordinates

The exposure command is given - depending on aircraft's speed, camera type and exposure time - about half a second before reaching a preprogrammed exposure station. This is because of the rotary shutter principle. The exact actual coordinates of the exposure station are computed by means of interpolation from the camera's feedback signal which indicates the exact actual time of shutter release. The coordinates may be annotated on the film, but will in any case be recorded on the project's cassette. Annotation of the exact coordinates of exposure stations and other data on film has been realized for the WILD RC-10A camera s. figure 4.

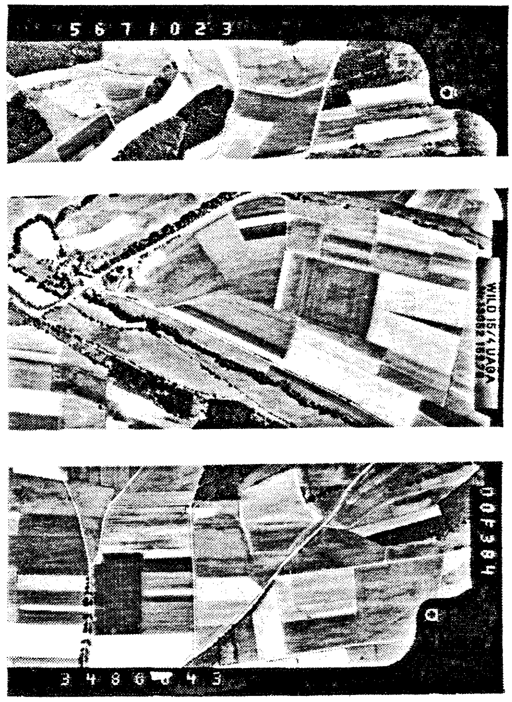


Fig. 4: Data annotation on film, WILD RC-10A aerial camera

8. CPNS OPTIONAL SYSTEM

The optional system is illustrated in figure 5.

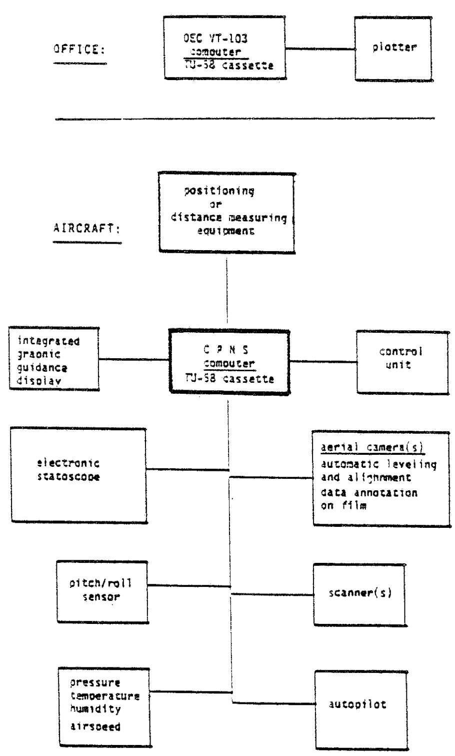


Fig. 5: CPNS optional system

8.1 Advanced Computer Supported Mission Planning, Automatic Flight Checking and Photo Administration

By means of a DEC VT-103 computer/terminal, equipped with cassette station, mission planning can be carried out in the office. One cassette can be prepared per survey mission. On a plotter (e.g. A3 size) a control plot can be produced to see whether the mission planning is correct and complete. The 'mission cassette' can be introduced into the CPNS computer to take over the mission parameters. The same cassette is used to record the actual flight parameters. After flight the same cassette is put back into the VT-103 computer in the office and automatically a flight index will be plotted.

For large projects to be flown under unfavourable meteorological conditions, complete photo management is possible. Photos may be accepted or rejected so that the camera shutter is released only at positions where a photo was not yet accepted.

8.2 Measurement of Delta Z (Electronic Statoscope)

High precision electronic differential pressure sensors are existing nowadays. It can be expected that they will deliver at least the same high accuracy as the conventional type of statoscope which is having serious operational disadvantages. Such a modern instrument is now integrated into the CPNS in order to record 'delta Z' values for the exposure stations or to record 'delta Z' continuously for the survey flight path.

8.3 Automatic Camera Levelling and Automatic Camera Alignment

To realize automatic camera levelling and automatic camera alignment - both with an accuracy of ca. +/- 1 degree - an artificial horizon and a compass, both with electrical output, are integrated into the system. Camera alignment does mean not only the setting of drift but the alignment of the camera axis to the direction of the planned survey line on ground (desired track!).

The record of 'pitch' and 'roll' of the aerial camera at the instance of exposure allows to plot the flight index according to principle points rather than perspective centres only.

8.4 Integrated Graphic Guidance Display, DR-Navigation Capability

In case additional sensors, as indicated in figure 5, are integrated into CPNS, an integrated graphic guidance display can be realized.

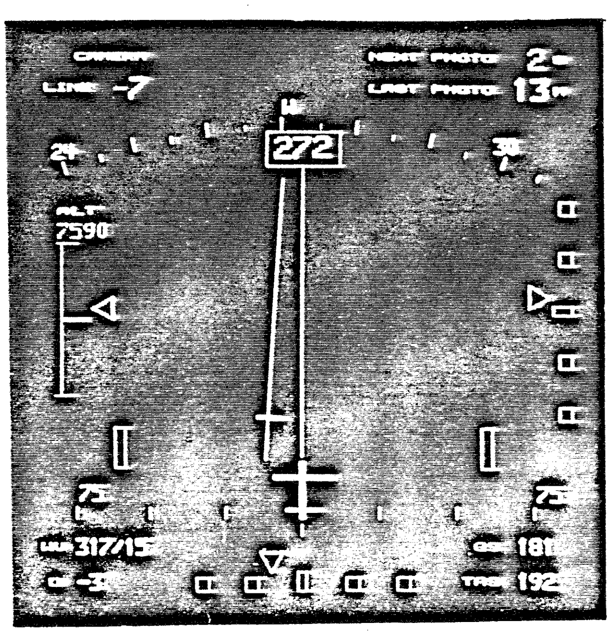


Fig. 6: Example of 'integrated graphic guidance display'

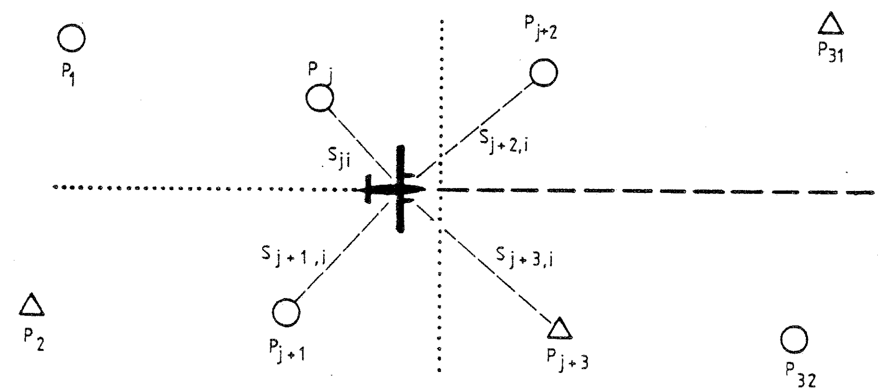
With respect to directional information it is more desirable to display magnetic heading information at the compass-rose rather than true track information (CPNS basic system, s. fig. 2), because heading is giving the pilot a better steering reference than track (delay effect)/2/. The integrated graphic guidance display allows the pilot to fly the airplane precisely without "scanning" any other flight instruments. Such an integrated display provides in addition DR-navigation capability, the advantage being that in case of occasional signal losses of the positioning or distance measuring equipment, the flight can be proceeded in DR-navigation mode.

8.5 Autopilot Control

In order to fly the airplane along the survey lines on autopilot control, CPNS can be coupled to the autopilot. The necessary data (cross track error and track angle error) are computed by CPNS with high accuracy.

8.6 In-Flight Calibration of Distance Measuring Network

To obtain maximum accuracy from a VOR/DME, TACAN or Thomson-CSF TRIDENT-III network, in-flight calibration of the network is necessary.



P_j = beacon position, △ known geodetic position
○ unknown position

P_i = range measurement positions on aircraft's track

The aircraft is guided along indicated track lines, range data recording and computation of network calibration is done automatically. As result of the in-flight calibration the following unknowns are determined:

- time delay (resp. constant range value to be substracted, range correction) for each individual transponder beacon,
- scale correction resp. correction factor for electromagnetic wave propagation speed (at least two beacon positions have to be determined with geodetic accuracy),
- corrections for position coordinates of transponder beacons according to weight factors.

From the following basic formula

$$S_{ji} = \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2}$$

X_j, Y_j = coordinates of beacon positions

X_i, Y_i = coordinates of range measurement positions

the correction equations for the least square adjustment can be derived.

$$v_{ji} = ds_j + S_{ji}dm - \frac{X_i - X_j}{S_{ji}}dX_j - \frac{Y_i - Y_j}{S_{ji}}dY_j + \frac{X_i - X_j}{S_{ji}}dX_i + \frac{Y_i - Y_j}{S_{ji}}dY_i - (S_{ji} - S_{ji_o})$$

ds_j = constant range correction for beacon P_j

dm = scale correction

dX_j, dY_j = correction for coordinates of beacon positions

dX_i, dY_i = correction for coordinates of aircraft's range measurement positions (additional unknowns)

S_{ji} = measured ranges (plane distances in geodetic coord. system)

S_{ji_o} = computed ranges (from approximate positions)

8.7 In-Flight Determination of Ground Control Points with TRIDENT-III Network

The mathematical model for calibration of a beacon network directly allows to determine coordinates of ground control points. In case these coordinates are to be in the geodetic coordinate system, at least two beacon positions must be known in this system.

Ground control determination can be combined with net calibration but it is also possible to determine ground control points within an already calibrated beacon network. Investigations to find optimal solutions for point determination can be carried out in simulation.

9. EXPERIENCES

Since 1982 a lot of in-flight testing of CPNS has been carried out.

9.1 Test Mission BODENSEE 1982

The Thomson-CSF TRIDENT-III range measurement system had been tested to evaluate its suitability for CPNS. A photo mission (48 x 10 Km², 1:15ooo WA, 240 photos) was flown without visual reference. The mission was carried out by means of a Dornier SKYSERVANT aircraft of DFVLR, Oberpfaffenhofen. The four ground transponder beacons were about 70 Km apart (s. fig. 8).

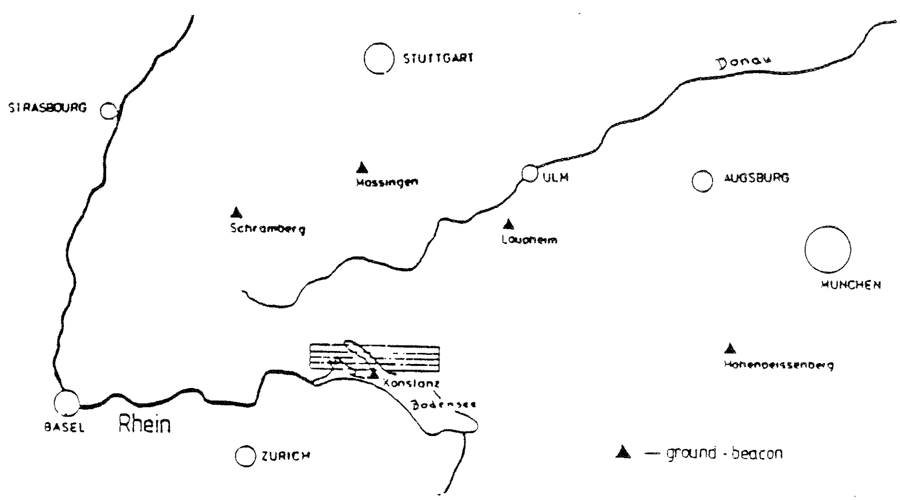


Fig. 8: Test mission BODENSEE 1982

The airborne computer was a HP-9825 providing left/right indication on a TDI (track deviation indicator) needle. The standard lateral deviation from planned survey lines was +/- 38 meters. Slant range measurement data had been recorded before and after the instant of exposure to be able to compute postflight the coordinates of the exposure stations. This was done in combination with a network adjustment calculation. The standard deviation of measured ranges (between 25 Km and 100 Km) was +/- 1.0 meter. The coordinates of exposure stations have been introduced as auxiliary data for aerial triangulation (PAT-M-43) by Prof. Ackermann /1, 19/.

The following conclusions had been drawn from this test mission:

- The Thomson-CSF TRIDENT-III is most suitable for CPNS.
- A powerful computer is necessary to solve the demanding computational problems in realtime.
- To obtain good range performance, the transponder beacon antennas have to be put at suitable positions.

9.2 Test Mission HOCHSAUERLANDKREIS 1983

Whilst the Bodensee mission has been carried out to test whether the Thomson-CSF TRIDENT-III would be suitable for precise aircraft positioning, the mission "Hochsauerlandkreis" was to test the CPNS prototype. For this a project could be taken over from the Landesvermessungsamt Nordrhein-Westfalen. The project was to produce pin-pointed aerial photography in scale 1:12500 for orthophotos 1:5000 (map size 2 x 2 Km²); the area covered 420 map-sheets. The mission was carried out by means of the Piper Navajo Chieftain aircraft of the ITC /2, 18/.

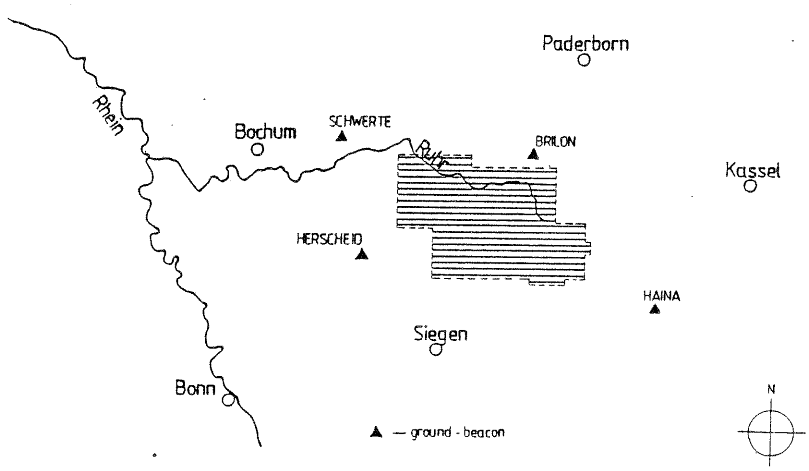


Fig. 9: Test mission HOCHSAUERLANDKREIS 1983

It could be demonstrated, that - under CPNS control - a lateral piloting accuracy of +/- 20 m rms can be expected and pin-pointed aerial photography can be obtained with an accuracy of +/- 20 meters.

Besides the aerial photographic mission flights, four extra flights have been carried out in the Hochsauerland area for range performance tests. Figure 11 shows as an example the result of one range performance test flight. For all tests, antennas of the 180 deg. directional type have been used. As a conclusion it can be stated, that the range performance of the TRIDENT-III can be predicted according to the topography in the vicinity of a beacon and according to flight altitude. The range performance obtained during the test flights were about 15% more than could be expected from the line of sight.

Fig. 10: CPNS operation in the Piper Navajo aircraft of the ITC-Enschede

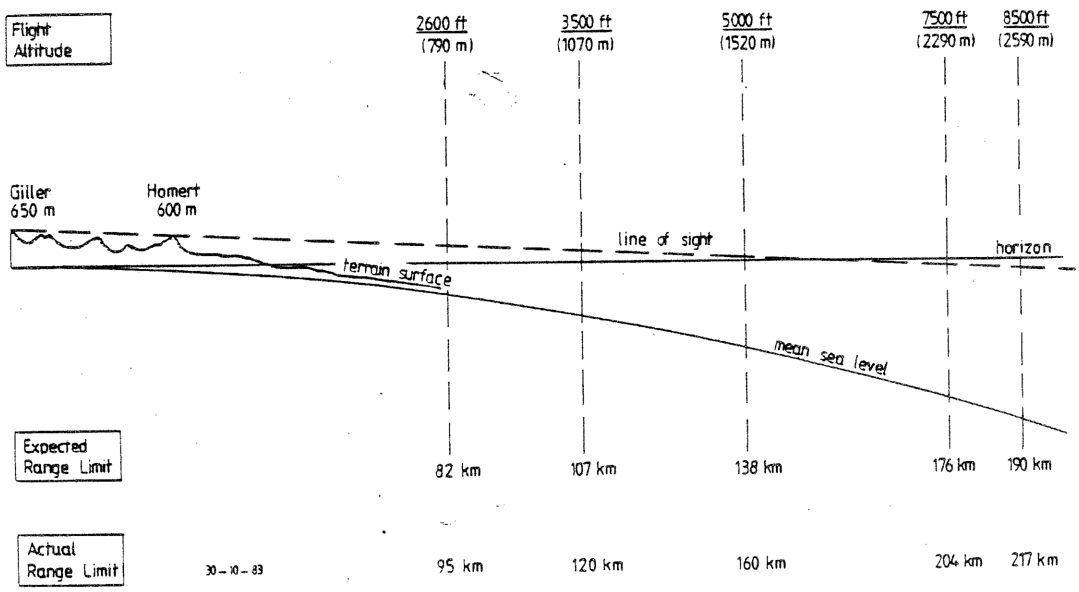


Fig. 11: Range test flight November 1983; beacon at Giller, TK 346

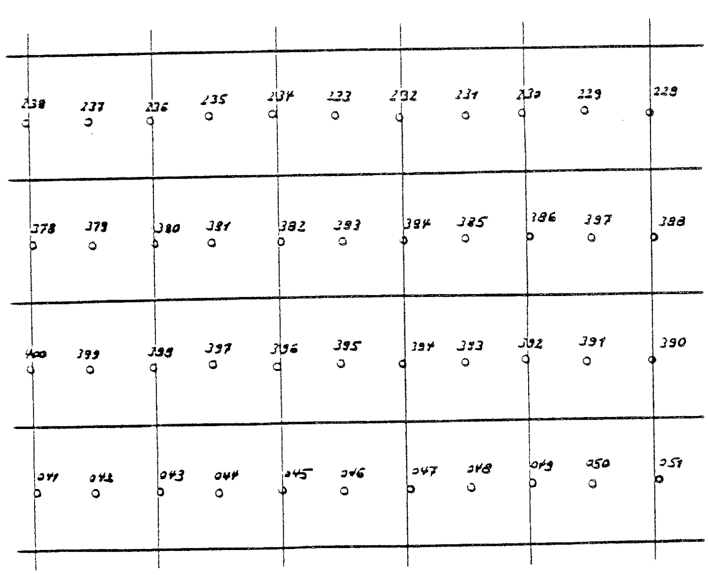


Fig. 12: Photo index of part of the HOCHSAUERLANDKREIS 1983 mission: principle points with photo numbers and map sheet lay-out. Lateral piloting accuracy +/- 16 m rms.

9.3 Test Mission OLPE-SIEGEN 1984

In spring 1984 a photogrammetric block of 30 x 60 Km² is flown in photoscale 1:27ooo twice:

a. based on Thomson-CSF TRIDENT-III, with a four beacon network and

b. based on VOR/DME, TACAN network and a Rockwell-Collins DME-700 receiver.

In case of 'test a' the saving of ground control is to be investigated. In case of 'test b' the performance of CPNS based on VOR/DME, TACAN equipment is explored. For both tests a previous in-flight net calibration is carried out and the new electronic statoscope is investigated.

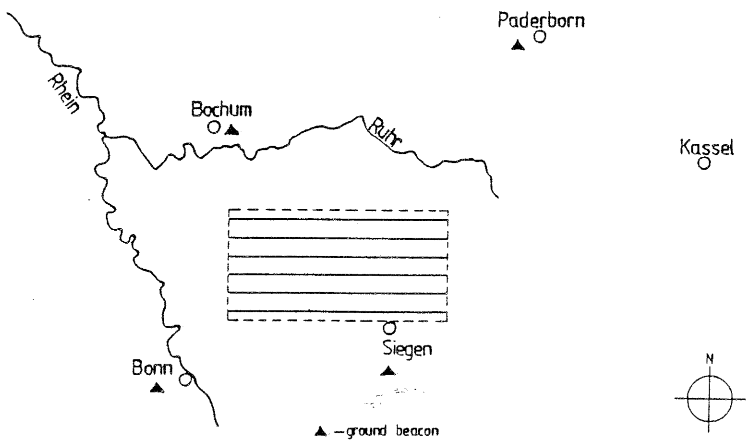


Fig. 13: Test mission OLPE - SIEGEN 1984

10. CONCLUSIONS

Flying for aerial survey has to become much more efficient than it has been until now. This is first of all important because of the fact, that flying as well as photographic material is becoming more and more expensive.
The need is growing for larger scale photography. A standard product will be the orthophoto; the orthophoto will also help solving the problem of map revision. Large scale photos will have to be taken at given air stations at regular time intervals. Pin-pointed photography is required according to map sheet layout. Computer-controlled photo navigation based on positioning which fulfils the respective accuracy requirements can increase the efficiency of flying for aerial survey drasticly.

Airplanes with a one- max. two-men crew can be used /17, 18/. No special survey navigation flight experience is required! Overlap regulators and heavy navigation telescopes can be deleted from the airplane. The saving of ground control points for aerial triangulation /1, 19/ is another, very important aspect.

Computer-controlled photo navigation - ideally based on fixed beacon network (until the availability of precise satellite positioning) - can revolutionize the efficiency of flying for aerial survey and remote sensing.

11. ACKNOWLEDGEMENT

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CPNS is now manufactured by IGI Ltd., 5912 Hilchenbach, W-Germany.

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