PERFORMANCE
OF NAVIGATION SYSTEMS AND OF SENSOR ORIENTATION SYSTEMS IN AERIAL SURVEY

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Remark 1: This paper is directly related to Invited Paper nr.2 by the same author, entitled < Applications of navigation systems and of sensor orientation systems in survey navigation, in aerial triangulation and in establishment of control>

Remark 2: Because of space limitations for the Archives, the original paper had to be reduced considerably. The complete paper, 80 pages, under the same title, is available from ITC on request - free of charge.

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ABSTRACT

This publication - the first of two invited papers - presents a condensed review of the state of the art in survey navigation and in determination of the elements of exterior orientation of the sensor at the instant of exposure.
The second invited paper will present a condensed review of the applications of their potentialities.

1. INTRODUCTION

During the last decades high technology has provided us with powerful methods and instruments for navigation and for determining the position and orientation of any object in the air mass or in space. The majority of these methods and instruments are available off-the-shelf; some of them are still being refined to a state of highest performance.

Until now, aerial survey has not made use of this instrumentation - except in isolated cases as "auxiliary instruments" for aerial triangulation.

It is high time to make an inventory of high technology which is available to us - as is done in this Invited Paper nr. 1 - and to analyse in which way the new possibilities can be put to economical use - as is done in the subsequent Invited Paper nr. 2.

2. DEFINITIONS

"Navigation" is the process of directing the movements of a craft from one point to the other. Navigation involves coordinates of position, direction, time and speed.

"Sensor orientation" is the process of determining the orientation of the sensor in space. Sensor orientation involves the six elements of orientation determined by three coordinates (e.g. position X and Y, altitude Z) and three angles (e.g. verticality ϕ and ω, azimuth or heading κ)

NOTE: In case the sensor is a photogrammetric camera, it has nine elements of orientation: three elements of inner orientation (the position, x,y of its principal point, and the value c of its principal distance or calibrated focal length, together with its associated distortion function) and six elements of exterior orientation (three position elements X, Y, Z, and three attitude angles ϕ,ω,κ)

3. TYPES OF NAVIGATION

Basically, the types of air navigation can be grouped in three classes: contact navigation (3.1), deduced reckoning (3.2) and position fixing (3.3)

3.1 Contact navigation or pilotage

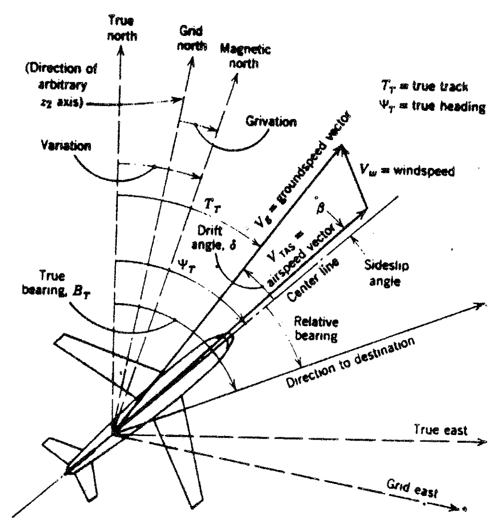
Contact navigation is the visual guidance of a craft along recognizable features (e.g. roads, rivers) or along a visually defined path (e.g. indicated on a map or mosaic).

3.2 Deduced reckoning

Deduced reckoning ("dead reckoning", DR) is an extrapolation of a "known" position to some future time, by means of direction (e.g. heading and drift) and distance (or: speed and time).

3.3 Position fixing.

Position fixing is the determination of the position of a craft either by means of "pinpointing" (i.e. observation of a recognizable landmark) or by means of using two (or more) "lines of position" (l.o.p's) (such as circles, hyperbolae, straight lines, radio beacon axes, railroad tracks or rivers) or by means of using three or more surfaces (such as position fixing by means of navigation satellites)



ELEMENTS OF DEDUCED RECKONING (DR) NAVIGATION

Examples of DR instrumentation: gyromagnetic compass plus driftmeter, air speed indicator and analog DR computer, or: doppler radar plus precision compass and digital computer, or: inertial navigation system including inertial platform and computer. All dead reckoning systems are subject to error propagation and must be updated by means of position fixing.

4. TYPES OF NAVIGATION SYSTEMS

The systems and instruments can be grouped in: ground-based systems (4.1), self-contained systems (4.2) and integrated systems (4.3)

4.1 GROUND BASED OR GROUND SUPPORTED NAVIGATION SYSTEMS

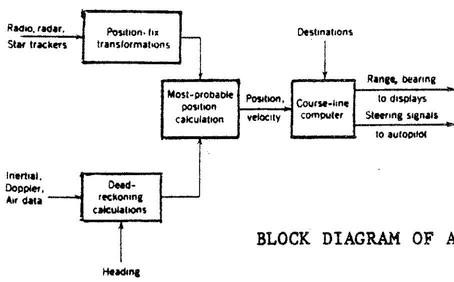
In case ground-based navigation facilities are available - such as ground features having a known position, radio beacons which can be us as "fixes", combinations of radio beacons which define a pattern of "lines of position" - they can be used for "position fixing" methods (3.3)

4.2 SELF-CONTAINED SYSTEMS

In case self-contained instruments are used exlcusively - such as compass, air speed indicator, drift meter, doppler radar, INS, etcetera, - "D.R navigation" (3.2) must be applied.

4.3 COMBINATIONS OF SYSTEMS. INTEGRATED SYSTEMS.

A combination of both types of systems (4.1 and 4.2) is most useful, because use can be made of the inherent short-term accuracy of DR (3.2) - whereby its inherent propagated error can be updated by means of position fixing (3.3).



BLOCK DIAGRAM OF AN AIRCRAFT NAVIGATION SYSTEM

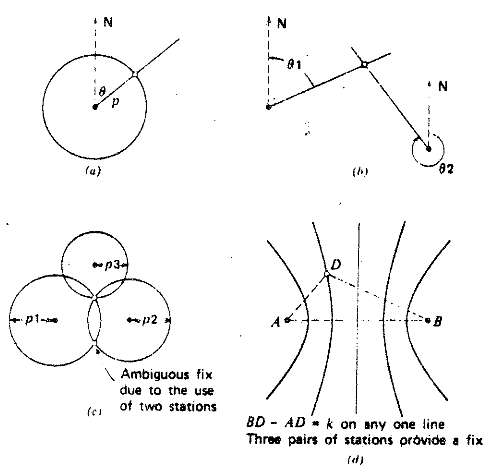
Where several navigation aids or sensors are available, it is possible to feed all of their outputs into one or more computers, which then provide a single output to pilot or to autopilot. One reason for integration is to improve reliability; in aerial survey, the major reason is to increase accuracy - e.g. updating a short-term accuracy system by means of a long-term constancy system. In case the combination of systems is such that they become mutually interwoven, the resulting system is called a "hybrid" system.
Examples: Doppler-radar-generated velocity used to update inertial -navigator-generated velocity, sometimes supplemented by the addition of intermittent fix correction by means of a radio navigation aid, (such as DME or Navstar).

5. TYPES OF SENSOR ORIENTATION METHODS AND INSTRUMENTS.

Modern flight instrumentation is not designed at the request of aerial survey. It is produced primarily for navigation - airborne or spacebound, military or civil.
Some of these instruments, however, may come in usefully to determine and to record the survey sensor's orientation elements.
In this review, they are grouped according to the orientation element they are sensing: position (X,Y), altitude or altitude difference (Z, dZ), verticality attitude (ϕ,ω) azimuth attitude (κ), or combinations of these.

6. PHYSICS, PRO's AND CON's.

D.R. is the technique of calculating a position from measurements of velocity - starting off from a known position - by extrapolating estimated or measured ground-speed Vg integrated over time t when travelling at a true heading ψ. All methods of D.R. are subject to predominantly serious propagation of errors with time (as is INS) or with distance (as is Doppler) - rather than to systematic errors, whilst all methods of position fixing are subject predominantly to systematic errors. In practice, the largest part of the DR propagated errors can be reduced ("updated") by means of position fixing. The largest part of the systematic position fixing errors can be reduced by means of monitoring - i.e. placing a "monitor" (i.e. a position fixing receiver at a known position) and measuring the difference between the monitor's indicated and its actual (known) position; that difference is the local and instantaneous systematic error of the "fix", which can then be used to correct the indications of the position fixing instrument aboard the aircraft for its systematic error. Doppler radar (in combination with the compass) - measuring drift and ground speed and calculating present position (see para. 7.1.5) - and inertial navigation systems - measuring accelerations and azimuth and calculating speed, distance, verticality, heading, present position and other navigational elements (see par. 7.7.1) -are the most sophisticated DR systems. Both are self-contained.



COMMON GEOMETRIC FIXING SCHEMES

(a) Rho-theta (ρ, θ) provides a unique fix from a single station; the l.o.p.'s always cross at right angles.

(b) Theta-theta (θ, θ) provides a unique fix from two stations. Geometric accuracy is highest when the lines cross at right angles and is poorest near the line connecting the stations.

(c) Rho-rho (ρ, ρ) provides an ambiguous fix from two stations, and a unique fix from three stations.

(d) The hyperbolic systems uses l.o.p's that each are the geometric locus of a constant difference in distance to two stations. Three pairs of stations are needed for a unique fix, though, for many practical applications, three properly located stations may suffice. The geometric accuracy is very much a function of the relative station locations.

7. METHODS AND INSTRUMENTS AND THEIR PERFORMANCE

Of the very many navigation methods, instruments and facilities, we will mention only those which may be of practical interest for aerial survey - now or in the near future. They will be grouped according to the parameter which is obtained as output.

NOTE: In this treatise, accuracies which can be reached are expressed in terms of "performance". In case errors are distributed in the "normal" way (Gauss distribution), errors smaller than the "standard error" (σ = one sigma) will occur in less than 66% of the cases, 2σ in less than 95% and 3σ in less than 99% of the cases. In aviation, the errors often have a non-standard distribution. "Performance", then, is defined as the values which are obtained in at least 95% of the cases.

7.1 PLANIMETRIC POSITION

7.1.1 Distance measuring equipment (DME) in combination with VOR, VOR/DME

In controlled airspace, VOR stations define the axes of the airways.
VOR ground stations located with a distance measuring system (DME) form the standard ICAO rho-theta short-range navigation system (UHF band, i.e. line of sight). [4]
In general, for survey navigation, VOR is not sufficiently accurate, but DME produces distances with a one-sigma error = 0.1 nm (= 200 m). Multi-DME fixes could have a one-sigma error below 100 m. In survey practice, however, a combination of several DME stations often is not available within short range of the survey area.

7.1.2 VLF-Omega

The VLF and the Omega system are both ground based hyperbolic low frequency systems, providing global navigational coverage. [4]
As in all circular and hyperbolic systems, the navigational accuracy is highly dependent on the position and the mutual configuration of the transmitters and the receiver. In photographic survey practice, the performance may range from 400 m (in very favourable cases only) to 1500 m, useful for photo scales 1:40 000 ~ 60 000. The performance of VLF can be increased to a high accuracy navigation system by positioning an extra frequency-stable beacon near the survey area.

7.1.3 Airborne tellurometer or Aerodist

The airborne tellurometer range measuring system is a high speed version of the hydrographic tellurometer system (UHF band, line-of-sight).
It is applied with two (or three) master stations in the aircraft and two (or three) beacons at known positions on the ground, producing rho-rho data. Its major application has been to produce extension of ground control. After adjustments for station elevations, for radio propagation velocity and for other parameters it has produced results with standard error in control points $\sigma = \pm$ 2m, depending on station configuration and on distance. [7, 8]
After the advent of satellite doppler the use of Aerodist has decreased because satellite doppler positioning requires considerably less logistics effort.

7.1.4 Triple and quadruple microwave beacon systems.

A Trident III (Thomson-CSF) positioning system operates on VHF - the 230 MHz version having a maximum range in the order of 300 Km, the 1219 MHz version of about 150 km. The one master station in the aircraft operates with four ground beacons. The outcome of aerial triangulation withing the 4-beacon-polygon is $\sigma = \pm$1m, outside that polygon it is of the order of 3 m. [16, 17, 19]
When navigating pre-computed pinpointed photography in combination with CPNS, the system produces nadirs within $\sigma = \pm$ 100 m of the desired ones.

7.1.5 Doppler radar

A Doppler navigation system is a self-contained DR system which measures ground speed and drift, plus vertical velocity if desired. In combination with a precision heading reference (e.g. a gyrosyn compass system) a navigation

computer can supply all desired navigational information except for the pitch and roll angles, i.e, the verticality.
In aerial survey, a modern Doppler navigator coupled onto a high-quality heading reference and a digital navigation computer can have error as in [6, 9, 13]. Doppler is not sufficiently accurate to serve as indicator for the sensor's orientation elements X and Y (planimetric position). For survey navigation, it is very well suited even for the larger scales. When intermediate updating is applied by means of the wellknown technique of sketching next-line recognisable landmarks shortly before any 180° turn, blocks of nearly any size and any number of lines can be produced free from gaps, up to photo scale 1:10.000.

7.1.6 Computer controlled photo navigation system (CPNS)

CPNS is a navigation computer and interface; it can be based on any navigation sensor, airborne or ground-based positioning system e.g. for large scales on Tellurometer, Motorola, Sercel Syledis, or Thomson Trident, for medium and small scales on Doppler, INS or VLF Omega, and - at a later stage - on GPS Navstar. Basic functions are (a) computer-supported mission planning and photo administration (b) aircraft guidance based on standardised survey flight procedures, and (c) pin-pointed aerial photography coverage - according to mapsheet lay-out - for orthophotomapping.
The performance of the system depends largely on the primary navigational or positioning system which is chosen. [18, presented at this congress]

7.1.7 Side sighting

A basic method of updating when flying parallel lines by means of DR is the well-known "side sighting".
Side sights were constructed in USSR [1], and by Fairey (outside bars), Corten (collimated sight), Gleize/IGN (méthode de l'arc capable), Corten and Heimes (gridline in Zeiss telescope), and others.
Its capability is to update all DR (including Doppler and INS) to 5% of sidelap in flat and to 10% in mountainous terrain.

7.2 METHODS PROVIDING ALTITUDE (Z coordinate, or dZ)

(a) Absolute altitude, above m.s.l., flight "altitude".

7.2.1 Barometric altimeter

The accuracy in absolute altitude above mean sea level - as determined by barometric means - is relatively low; in the best cases we may come as close as 10...30 m, depending on the availability of atmospheric data.

(b) Relative altitude above terrain, flight "height".

7.2.2 Radio (or radar) altimeter

The radio altimeter is used primarily when approaching the runway, at the pre-landing stage. Its accuracy is of the order of only 2 percent; also, its beam is very wide, except when used as "airborne profile recorder" (APR). For various reasons, radar APR is now superseded by the laser APR.

7.2.3 Laser altimeters

A laser beam has a nearly negligeable beam width (spread) and keeps its intensity over a long distance. In aerial survey, laser altimeters are used in combination with a precision differential altitude recorder and with a terrain profile recorder. The accuracy of laser measurement is extremely high, it can be in order of centimeters - approximately 3 cm or 1:10.000 whichever greater. In practice, the roughness of the vegetation profile will be the limiting factor rather than the laser itself.

(c) Altitude differences and differential altitude.

7.2.4 Statoscope, hypsometer, altitude transducer, baro/inertial differentials

The statoscope measures altitude differences by means of air pressure generating differences in electrical capacity. The hypsometer makes use of the differences in boiling temperature of a fluid - e.g. toluene - under varying pressure circumstances. The heart of Rosemount's altitude transducer is a capacitive pressure difference sensor. The baro/inertial differential altitude sensor is a combination of a sensitive barometric sensor with the vertical component of an inertial navigation system.

In all altitude difference instruments, the sensor's electrical signal output is processed and recorded - either photographically or graphically or digitally [20]. The inherent accuracy of the direct output can be better than of ± 1 m; after adjustment it is about ± 0,65 m. [50]

(d) Combinations of (b) and (c).

7.2.5 Airborne profile recoders (APR): Radar APR, Laser APR, Baro/ Lidar, Laser bathymeter, Laser tree heighter

Airborne profile recorders are hybrids composed of

1st: an instrument serving to let the aircraft maintain constant barometric altitude, and to measure and record the small deviations from maintaining that altitude - i.e. isobaric surface.

and

2nd: an instrument to measure the radar height or laser height of the aircraft above terrain, or forest canopy, or bush vegetation, or underwater bottom, or whatever surface can be used to let the radar or laser energy reflect and return to the aircraft.

The major sources of error are:

1st uncertainties in isobaric function of the actual atmosphere

2nd quality of the reflecting surface

3rd flight height of the aircraft - i.e. pressure lapse rate.

Consequently, the accuracy of APR can be expressed as the root mean square sum of the three above mentioned errors.

A new system - designed for Pow-altitude stream-valley cross sections and profiles - is the Aerial Profiling of Terrain (APTD) System, developed for the NSGS and under trial since february 1983. [60][61].

The system consists of an inertial measuring unit, a laser tracker (locking on to surveyed retroreflectors) a pulsed laser profiler, a video system and a computer. It is ground-based and requires updating every 200 seconds.

Performances to date are

aa:

Radar APR, adjusted, used to produce height control of large area:

- flat or rolling terrain, (no vegetation) $\sigma \approx \pm$ 1....2 m.
- mountainous terrain, (no vegetation) $\sigma \approx \pm$ 3....6 m.
- vegetation cover ... error according to type of vegetation [21, 22, 23, 24].

bb:

Laser APR in combination with 1:50,000 photography of large and heavily forested area, after block adjustment:

- terrain surface elevations (in-between trees) $\sigma \approx \pm$ 2m
- tree heights were recorded cleary. [25]

cc:

Laser APR tree heighting and bathymetry:

- tree heighting of tropical rain forest, 1% porosity in 99% forest cover.

. bathymetry: bay depth accuracy in the order of ± 15 cm was obtained. [55, 56, 57, 58, 59]

dd:

Laser profiler APTS:

. absolute horizontal performance ≈ ± 60 cm.

. vertical performance ≈ ± 15 cm [60, 61].

7.3 METHODS PROVIDING POSITION IN SPACE (COORDINATES X, Y, Z)

A realistic method which, in the near future, will provide instantaneous position of the sensor - in three coordinates - is the Global Positioning System (GPS) called Navstar.

7.3.1 GPS/Navstar

Navstar is a space-based navigation system, that will provide highly accurate three-dimensional position fixing and velocity information. The system is under construction and is expected to be fully operational by 1987.
Actual performance (2σ, 95% probability) is expected to be in the order of ± 10 m in planimetry, ± 15 m in altitude and ± 0.05 m/sec in speed.
This remarkable accuracy will be used to provide for the X, Y and Z coordinates of each aerial photograph's exposure station - these potentially being smoothed by a precision inertial system which uses the GPS data as fixes to become updated, or being introduced into an adjustment procedure together with whatever ground control may be available (see Corten "Applications...").
This accuracy, however, will not become available to civil aerial survey before the end of the 90's because GPS Navstar is developed as a military guidance system and will remain under U.S. military control for the time being: it is the intention - for civil use - to degrade the system to a performance of 80 or 100 m. [27, 28, 29, 30, 31, 32, 33].
Remarks: (a) Local use of GPS makes it possible to apply "differential navigation", i.e. positioning a stationary monitor within the area, generating three-dimensional "ground-truth", which is transmitted to the survey aircaft to correct her own GPS navigational solution. This method can effectively correct all major sources of systematic errors (in that particular area, at that particular instant). Differential navigation has consistently produced three-dimensional navigation positions in the order of 5 m
(b) The Sovjet Union plans to deploy a global navigation satellite system almost identical to GPS/Navstar and has started.
(c) Proposals are made by the European Space Agency to produce and operate a civil worldwide navigation-satellite system ("Navsat"). ESA's proposal has the advantage of being a non-military - and thereby less sophisticated - system which might be employed commercially.

7.4 METHODS PROVIDING VERTICALITY ATTITUDE (ϕ, ω)

7.4.1 Mechanical-electrical precision gyroscope

Precision gyroscopes have been used (a) to record the attitude of the aerial camera at the instant of exposure, and (b) to keep the camera's optical axis vertical during flight.

Ad (a)
The best performance obtained in verticality recording has been 10'. This is sufficient for rectification purposes but not for other photogrammetric use.
Ad (b)
Gyro-controlled verticality performance has never been sufficient for photogrammetric surveying.

7.4.2 Laser-gyro

Three ring-laser gyros are mounted mutually at right angles and measure the system's angular rotation in space. A computer converts these measurements into 'aircraft attitude'. The laser gyro might become more accurate and may, in any case, have still higher reliability than other present-day precision gyros.

7.5 METHODS PROVIDING AZIMUTH ANGLE (HEADING AND DRIFT)

7.5.1 Compass heading

In survey navigation, gyrposyn compasses is used mostly. They can perform to 1/2° for pilot's use, and to ± 0.2° when used in conjunction with an autopilot.

7.5.2 Visual drift sight, navigation sight

Drift angles can be measured by
- telescopic navigation sights or drift sights,
- Electro-optical driftmeter
- Doppler,
- INS

A visual navigation sight may provide drift angles to about 1 or 2 degrees, with considerable time delay of at least about 1 minute.
Doppler and INS provides drift to ± 0.3° performance instantaneously. The conventional "navigation sight" suffers from serious errors due to roll, due to heading changes and due to time lag. The Zeiss sight is converted into a "side sight" by means of the ITC next-flight-line grid.

7.5.3 Electro-optical drift meter

The time lag error is reduced considerably by Zeiss electro-optical drift sensor and indicator. It senses the forward V/H ratio as well as the across-line V/H ratio, the vectorial component of these two being the drift vector. At the time of this writing it is under trial in various countries, over various types of terrain. Results will be reported upon in this WG I/3. (poster session).

7.5.4 Doppler drift

Basically, Doppler produces drift and ground speed - instantaneously. A drift indicator at the pilot's panel is very usefull, as well as hooking the autopilot onto the Doppler navigation computer. For Doppler radar see paragraph 7.1.5.

7.5.5 INS drift

One of INS outputs is instantaneous drift which will be fed into the flight director system. For INS see paragraph 7.7.1.

7.5.6 Azimuth angle, flight axis' northing, camera's drift correction angle, kappa κ

Compass heading minus drift correction angle provide the flight axis (track).
Differences between the photographs' principal points' axes become apparent in photogrammetric restitution easily as differences in κ.
Kappa orientation is fast and accurate; for this reason there is no real need to record κ at the instant of exposure.

7.6 METHODS PROVIDING COMPLETE ATTITUDE (ANGLES ϕ, ω, κ)

7.6.1 Horizon camera. Solar peroscope

These instruments are not in use any more.

7.6.2 Attitude reference system (ARS)

A highly accurate system to determine the angular attitude of a survey camera in space - designed for the space shuttle earth mapping mission using the large format camera (LFC) - consists of two stellar cameras rigidly attached to the LFC, directed towards the horizon. The ARS cameras are exposed synchronously with the exposure of each LFC frame.

By post-flight measuring of the identified stellar pattern it will be possible to determine the attitude of each LFC frame with an accuracy of $\sigma \approx \pm 5$ arc seconds about each of the three rotation axes.

7.7 METHODS PROVIDING THREE COORDINATES AND THREE ANGLES (X, Y, Z, ϕ, ω, κ)

Currently, the only practical method of this class is the inertial navigation system (INS).

7.7.1 Intertial navigation system

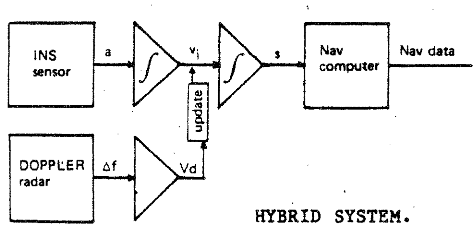
One of the instruments available for aerial survey is the photogrammetric integrated control system (PICS) which records, at each instant of camera exposure: position (X, Y, latitude, longitude); altitude or altitude difference (by integration with compatible altitude sensors); verticality attitude (pitch and roll angles ϕ and ω), compass heading (northing), drift angle (navigational drift or camera's drift correction angle). It records this data in numericals, along the photoframe and on magnetic tape, together with date, time, mission or job identification.

A remote control unit enables the navigator at the navigation sight to actually steer the aeroplane either over an "absolute fix" (known coordinates) or over a "relative fix" (recognisable point but coordinates unknown) for absolute or for relative updating or for parallelling the flight lines.

Manufacturers guarantee the performance of INS according to ICAO's (International Civil Aviation Organization) specifications for airline use, i.e. better than 2 nautical miles per hour at 95% probability level. Airlines use indicates that an instrument drift = 3 km per h. may be expected as actual performance (95%). [38, 39, 40, 41, 42, 43]

7.8 INTEGRATED OR HYBRID SYSTEMS

Hybrids of two components A and B are composed.
- either to improve the weak points of component A by means of component B and vice versa
- or to improve reliability



HYBRID SYSTEM.
Doppler - Inertial hybrid.

Examples of hybrid systems are:
- GPS-Navstar/INS: Navstar's high position accuracy may be used to update an INS.

- INS/VLF-Omega or Loran C: INS data can be permanently updated by a position fixing method having appreciable systematic error but relatively low random error.
  It is expected that integrated and hybrid systems will become more and more important. [4, 35, 42, 43]
  It is reasonable to expect that GPS/INS hybrids will play a vital rôle in aerial survey - to save ground control.

8. CONCLUSIONS

The state of the art, today, is that all navigational elements and all elements of the sensor's exterior orientation, as well as a number of differentials, can be measured and recorded - at the instant of sensing or photographic exposure.

This can be done in various degrees of performance.

There is no doubt that, in the near future, performance will still be increased considerably - for instance, by means of intergrated systems or hybrids (e.g. GPS/INS).

This development is revolutionising aerial photography (perfect navigation) and aerial survey (saving considerably on ground control).

9. REFERENCE LITERATURE

A list of 61 references is presented in Invited Paper nr.2 by the same author: < Applications of navigation systems and of sensor orientation systems in survey navigation,in aerial triangulation and in establishment of control. >

10. APPENDIX

This review is tabulated in Appendix pages 12a, 12b, 12c and 12d, each of these presenting one quadrant of the totality.

They should be arranged:

12a	12b
12c	12d

ELEMENT	PARA-GRAPHS	SYSTEM, METHOD	TYPE DESCRIPTION
X, Y planimetry position	7.1.1	Distance measuring equipment (DME)	Ground based beacons, used in aviation's controlled air space, standard ICAO rho-rho nav.system, UHF band
	7.1.2	VLF-Omega	Ground based hyperbolic system, global coverage, VLF band
	7.1.3	Airborne telluro-meter, Aerodist	Ground based rho-rho system, 3 beacons, UHF band, line-of-sight
	7.1.4	Microwave beacons	Triple and quadruple microwave ground beacons, VHF band (Thomson-CFS Trident, Motorola, Sercel Syledis, etc.)
	7.1.5	Doppler Radar	Self-contained (airborne) measure-ment of aircraft's ground speed and drift; coupled onto precision head-ing reference and onto navigation computer it produces all navigation-al information.
	7.1.6	Computer-Controlled Photo Navigation System (CPNS)	Navigation computer fed by any navigation sensor or positioning system, used also for extension of control
	7.1.7	Side sight and pre-computed turns	Visual DR, updating by maintaining proper line spacing; side sights, slide rules, turn graphs
Z "altitude" above m.s.l.	7.2.1	Barometrtic altimeter	Self-contained flight instrument
Z "height" a. terrain	7.2.2	Radio or radar altimeter	Self-contained flight instrument
	7.2.3	Laser altimeter or bathymeter	Self-contained
dZ altitude differences	7.2.4	- Statoscope, - hypsometer, - alt. transducer, - baro/inertial alt. differential	Self-contained
Z plus dZ	7.2.5	Airborne profile recorders: - Radar APR - Laser APR - Baro/lidar - Laser bathymeter - Laser tree heighter - Laser profiler APTS	Self-contained, recording both deviations from isobaric surface and height above terrain and/or canopy and/or water surface and/or water bottom.

SYSTEMS AND METHODS IN AERIAL SURVEY

USE FOR NAVIGATION FOR SENSOR ABS.OR. AS PARAMETER IN A.T.	PERFORMANCE 2σ ≈ 95% (order of magnitude) ERROR BEHAVIOUR	REFERENCE AUTHOR	REMARKS
Navigation only	- Direct performance ≈ 400 m. - Multi-DME fixes performance (by 5-channel)≈ 200 m.	General experience in aviation [4]	Often not available where needed.
Navigation only	- Performance depends on distance from ground stations and on configuration; in favourable cases ≈ 400 m but normally to 1000 or 1500 m ≈ 1 : 40 000... 60 000.	[4]	
Extension of planimetric control, needs terrain elevation data	Procuces control up to accuracy σ≈ ± 2 m, depending on stations configuration and distance	[7, 8]	Since advent of satellite doppler: obsolete (logistics.)
- Sensor orientation, planimetry obtained after triangulation - Navigation, coupled onto CPNS	Produces control up to accuracy σ ≈ ± 1 m within a 4-beacon polygon σ ≈ ± 3 m outside polygon. pre-computed pin-pointing ≈ 200 m	[16, 17, 19]	Planned to construct permanent beacon network in France
Navigation only	Error propagates with distance from last fix, and with turns. Useful - without updating - to navigate gap-free 1:25 000 and - with updating by side sighting - to navigate 1:10 000.	[9]	Particularly useful in difficult and improperly mapped area
Navigation and planimetric control extension, aircraft guidance, pin-pointed coverage.	Performance depends on choice of basic positioning sensor, e.g. microwave beacons (7.1.4.)	[13, 18]	
Navigation only	± 5% of spacing in flat and ± 10% of spacing in mountainous terrain	[1], General experience in aerial photography	Also for updating self-contained Doppler and INS
Navigation only	10...30 m	Textbooks on avigation	Used to produce approximate photo scale
Navigation. Also used in airborne profile recorder (APR)	2% only In APR, performance 1...2 m on "hard" surface.	[4]	Used at approach to landing. Radar supersedet by laser APR
	Performance of laser altimeter or bathymeter in itself 3 cm or 1:10 000 whichever greater. In practice, the terrain is the limiting factor.	[55, 56, 57] [58, 60, 61]	
Use as auxiliary parameter in aerial triangulation is very effective	Isobaric surface being controlled (either by ground heights or by drift angles and Henry correction) statoscope gives σ≈± 1 m dZ.	[20, 26] [49, 50]	
	Performance of laser extremely high (7.2.3). Performance is limited by (a) uncertainties of isobaric surface, and (b) uncertainties of reflecting surface . Examples: Radar APR, flat or rolling terrain, no vegetation σ ≈ ± 1..2 m; same, mountainous terrain no vegetation σ ≈ ± 3.. 6 m Laser bathymeter, depth σ ≈ ± 15 cm ATPS positioned by laser tracker	[21, 22, 23, 24] [25, 49, 55, 56] [57, 58, 59, 60] [61]	

ELEMENT	PARA.	SYSTEM, METHOD	TYPE DESCRIPTION
X,Y,Z position in space	7.3.1	GPS/Navstar	18 earth-orbiting satellites, providing time-difference distance to the vehicle, rho-rho-rho system, global coverage
	7.3.2	USSR System	Similar
	7.3.3	ESA System Navsat	Simpler, for civil nav use only
φ, ω verticality	7.4.1	Precision gyroscopes	Self-contained, mechanical-electronical instruments
	7.4.2	Laser gyros	Self-contained
κ azimuth, heading, northing, drift, kappa	7.5.1	Compass to indicate aircraft's heading	Precision compasses only (e.g. gyrosyn compasses) are good enough for survey flight, for D.R., and for doppler coupling.
	7.5.2	Visual drift sight	Visual drift sight, with or without gyro control.
	7.5.3	Electro-optical drift meter	
	7.5.4	Doppler drift processed to track	Doppler drift indicator or direct coupling to autopilot.
	7.5.5	INS heading, drift and track	INS data are fed into navigation computer and autopilot and recorder
	7.5.6	Kappa recording	
φ,ω,κ complete attitude	7.6.1	Horizon camera	Photographic record
		Solar periscope	Photographic record
	7.6.2	Attitude Reference System (ARS)	Two stellar cameras integral with the mapping camera provide the attitude after stellar analysis.
X,Y,Z φ,ω,κ three coordinates and three angles	7.7.1	Inertial Navigation System (INS)	Self-contained, high technology mechanical and electronic and computer performance
Various	7.8	Integrated systems, hybrid systems	Combinations: Doppler, INS, Loran C, GPS, gyros, VLF, laser, baro, etc.

USE	PERFORMANCE	REFERENCE	REMARKS
Navigation and determination of position	Performance in precision mode (classified)≈ 10 m in X,Y,and ≈ 15 m in Z. Deteriorated for civil use to 100 m. Performance in differential mode (monitor) can be used as parameter in triangulation adjustment, with ground control - be it complete or non-existing. Research is carried out for use without ground control	[27].....[33]	Important development Is under way for 1987; not yet operational
Existing Similar use			
Similar use		ESA	Is proposed; not yet under construction
Sensor controlling and/or recording verticality	Best performance in practice ≈ 15 sexag. minutes	Textbooks on avigation	Not used to verticalise the optical axis but to record the deviations. For rectif.
	Performance not yet established. Will increase reliability.		Will become useful in INS and other systems
Navigation only	For pilot's use: performance in reading ½ degree; in electrical coupling, it should perform to ± 0.2°.		
Navigation only	Performs to one degree only under stable conditions of atmosphere and and aircraft. Performance around 1...2° with a time lag of appr. 1 min.	Wild, Zeiss	
Navigation only	Instantanuous drift (no lag).		
Navigation only	Instantaneous drift (no lag) to ≈ ± 1/3° performance, depending on compass.	para. 7.1.5	
Navigation	INS heading, drift and track are subject to instrument drift, approx. 2 sexag. minutes per hour	para. 7.7.1	
In photogrammetry			No need for recording in flight
Horizon camera was used in Finland. Needs good horizontal visibility to either the horizon or to cloud bank base line			Instrument not used anymore.
Solar periscope was used in Italy and N-Africa to provide attitudes as auxiliary data parameters for aerial triangulation.			Instrument not used anymore.
Used to determine the absolute orientation of the camera at the instant of exposure.	Highly accurate when used in space together with satellite's or space shuttle's orbiter data, attitude is determined to ± 5 arc secs about the three axes.	[47]	Designed for use in mapping from space (LFC) exclusively.
Designed for navigation In aerial survey INS scan be used to control flight and camera, as well as to serve as parameter in aerial triangulation	Direct performance: instrument drift 3 km p.hour. Used to control the survey navigation and the camera exposure stations. Used as independent additional parameters in aer.triang., together with full ground control, with incomplete ground control, and when no ground control is available.	[37, 38, 39, 40]	Efficient use as hybrid with other systems
		[34, 35, 41]	Expected to become and more important, accurate and reliable