Photogrammetrische Woche 1985
Institut für Photogrammetrie
Schriftenreihe, Heft 11, 1986

NEW MEANS FOR AIR SURVEY NAVIGATION

Ph. Hartl, Stuttgart

Introduction

There are two different tasks of navigation for photogrammetric missions:

- Precise guidance of the aircraft along its nominal track during its flight and control of the camera operation
- Post flight determination of the actually achieved flight parameters from the "auxiliary navigation data " for performing the geometric corrections to the orthophotographic products with a minimum number of ground control points.

The first task aims at a "one photo = one map sheet" /1/2/, by a production of photographs at preprogrammed positions. For this purpose the navigational aids must allow in real time:

- The determination of the actual flight data, such as position, velocity, heading etc.
- The transformation of these data into the proper guidance parameters for the identification and display of the deviations from the nominal track and for the proper correction procedures to be performed by the pilote or autopilote.
- The execution of the command to fire the camera at the preprogrammed a/c positions.
- Annotation of the navigational information at the photos.

The second task of the post flight determination of the geometric corrections to the photographic products requires

- very precise a posteriori position determination and
- very precise a posteriori attitude determination

as a function of flight time.

Because of the fact that for air survey navigation various systems are already available for practical applications and are described in various articles, it is the intention of this paper to concentrate on the second task.

So, in other words, it is assumed in the following that the actual flight has already been performed with high accuracy, be it by means of an air survey navigational system or by an experienced pilote. The "auxiliary data" of interest are assumed to be stored, for example, on tape, and are subsequently used by the photogrammetrist to perform the systematic correction on the photoproducts and to complement this work by means of only a few ground control points.

It is quite obvious that the auxiliary data must be of very high accuracy. The topic of this paper is ,therefore, devoted to the question, which navigational tools one can expect in the future for this purpose. Of course, this is not only of importance for the classical aerial photography, but plays an important role with respect to new types of sensors, such as the mechanically and the electronically scanning optical sensors, the laser and microwave profilers etc. It will be shown that there are two interesting developments in the relevant area of navigational aids, which must be looked at:

- The GPS-receiver technique and
- The Laser gyro techniques.

Existing Navigational Aids

The two types of information needed are

- the precise position of the aircraft as a function of time, and
- the three parameters determining the orientation of the camera during the flight, such as pitch, roll and yaw, or some equivalent information.

Let's consider first the position measurement. It is possible to discriminate between the inertial navigational aids, the radio navigational aids, and some combinations hereof. Of course, one could also apply the photo-products themselves for the determination of the aircraft's position and attitude. But this is not considered here as being well known and very tedious. And, as a matter of fact, it is the purpose of this paper to show ways, how to reduce the effort for this classical photogrammetric task.

The inertial technique is well known as being expensive. It is commercially available, for example as ITGS/PICS, or GEO-SPIN a. o. and used with success primarily for the real time navigation task. It can deliver filtered information for postflight position and attitude determination. The accuracies are in the order 1 NM per hour in the two horizontal coordinates and in the order of 1×10^{-3} to 1×10^{-4} rad. It is obvious that such a system required updating by other means, be it by photographic or radio system support. In addition, inertial systems deliver only the two-dimensional position co-ordinates x, y. The altitude information must be acquired by different means, for example by an altimeter. It must be emphasized here that there is the tendency to replace more and more the mechanical inertial techniques by laser gyro techniques, whenever possible. This technique will be discussed later in this paper.

The radio navigational aids can be divided into those, which are ground based and those, which are space based. The ground based systems can either rely on existing radio navigation systems, such as VOR/DME, TACAN, LORAN-C, SHORAN, DECCA, OMEGA, etc, or they can apply local networks, which are to be established by means of portable ground station, like the Thomson-CSF TRIDENT-III system /3/. The first alternative has the advantage of requiring very little additional effort. Its disadvantage is the limited accuracy, which is in the order of tens of meters or more. The second alternative offers relatively high accuracy, namely in the order of meters, but requires a set of beacons to be displaced over the region to be surveyed. The number of beacons depends on the aircraft's h1 and groundstation's altitudes h2, on the required accuracy etc.

With these ground based terrestrial aids again only the horizontal coordinates are determined. The altitude has to be measured with other means, such as the electronic statoscope.

GPS-NAVSTAR-SYSTEM

As a new method the space-based GPS-NAVSTAR system has to be considered. For the position determination it has the following advantages:

- It is worldwide available
- It offers very high accuracy
- It delivers three-dimensional information of position and velocity.
- It omits largely tropospheric propagation errors, as the signals are propagating from space to the aircraft; signals of low elevation, which would be affected not only by delay but in particular by refraction, can be avoided.
- It is based on electronic instrumentation, which shows the apparent feature of continuing cost reduction and increasing large integration, which leads to mass products of very small size. As a matter of fact, one can expect in about 10 years from now that GPS-receivers of modest accuracy (40 m to 300 m accuracy, 20 m to 40 m precision) might have the size between a cigarette and cigar box and might cost about one or a few thousand dollars a piece. Presently this technique is, however, still very expensive. In addition, the GPS-system will be introduced during the next years as an operational system with considerable modifications to meet the protection requirements of the military. But, the following statements and conclusions will, most probably remain true and can be considered as general guidelines for the envisaged development.

The important features of the GPS navigational system are shortly summarized by means of table 1. In fig. 1 are shown the various orbits of the 18 satellites, which will be launched during the next 3 years, in order to constitute the operational system. It is possible to predict and to measure the satellite's positions as a function of time. Updated information about the satellites will be permanently available at each GPS-receiver. At any instant the satellites can be considered like fixed transmitters (ground stations) of conventional navigation systems.

By means of atomic clocks the satellites are able to transmit the ranging pulses and the frequencies with very high precision. With ranging signals of 4 satellites one is able to determine socalled "pseudo-range" positon and the local time; fig. 2.

The error budget is given in tab. 2. Apparently one has to descriminate between two receiver techniques, the so-called C/A-code-receiver and the P-code-receiver. The first one is the less expensive one with modest accuracy, the second one is of "high precision" and is much more expensive.

For the photogrammetric needs of position determination it will be sufficient in most cases to apply the C/A-code receiver. Of particular interest in this context is the fact that the accuracy of the position determination can be considerably improved by applying the C/A receiver not only in the aircraft but, in additional also at the optical reference points on ground. In this case one can compare a posteriori the GPS-measured co-ordinates of the reference point(s) with the "true" value, in order to determine the local error of the GPS-system and then one can use this value to correct the airborne measured position. Most of the systematic error will then be excluded and the position accuracy of the aircraft will become known to a few meters.
If a receiver is available at the reference point(s) then one can at least compensate some of the systematic error by just comparing the nominal coordinates before and after take off at the airport with the GPS-onboard measured co-ordinate values.

Attitude Control

The requirements to attitude control are much more severe in photogrammetry than to position determination. Table 3 summarizes the required accuracies for various photogrammetric applications (result of private communications with A. Ackermann). Although these very ambitious objectives will not be achieved in the near future with GPS-techniques, I want to consider, at least, the ultimate accuracy, which one can expect and can aim at. In fig. 3 it is assumed that the two rotational axis for roll and pitch could be used in an aircraft as mechanical baselines of, say 10 m in length (which is realistic for the two horizontal lines). One could install at each end an antenna and preamplifier and connect it with the receiver, located at the centre. The receiver must, in this case, be a P-code receiver, in order to allow to solve for phase ambiguities.

Let's consider first only one of the axis; fig. 4. For the signal of satellite S1 the phase shift (or the equivalent time delay) of the two signals received in antenna 1 and 2 resp. is a function of the incidence angle:

$$\phi = \text{arc sin} \left(\frac{\Delta}{b}\right)$$

With this interferometric device one could measure very precisely the relative attitude of the baseline. For example:
Assume that the phase difference is measured to about 1/100th of the wavelength, which is 20 cm for the GPS-L1 carrier signal. The deviation of 0,1 cm/1000 cm = 1×10^{-4} rad would then be the equivalent maximum angular resolution. This is not far from the above stated wishes of the photogrammetrists.

Several important assumptions have been made, however:

- The geometry must be close to optimum, i. e. the satellite must be located vertical to the baseline.
- The multipath effects must be avoided (only direct signals are received from the antennae, no reflected ones).
- The elevation of the satellite must be such that the refraction of the signal by the troposphere and the ionosphere can be neglected.
- The internal error sources (different signal delays in the different instruments) are negligible or are, at least of the same character, which would lead to a cancellation of the affects, etc.
- The signal to noise ratio is good enough, which requires good filtering.

If one takes into account that at least one of the minimum 4 satellites in view is close to the local zenith, one could use this s/c for the determination of roll and pitch angle determination. For the yaw angle it would be preferable to use one or more of the satellites sufficiently close, but not too near to the local horizon, for example with an elevation angle between 10 and 30 degree. In addition one should choose only satellites, which offer a "good" geometry: Direct line of sight from the antenna to the GPS-satellite, no reflecting or shadowing structural parts of the aircraft in the line of sight. One might argue that the vibration of the aircraft's structure and between the aircraft and the camera can drastically vary the geometry in comparison with one mm. But one can suppress the vibration signals, by proper filtering of the processed GPS-signals and concentrating to the average values. Although there is still some way to go before achieving the above stated accuracies (or resolutions), we think that it is worth wile to investigate this new attitude control scheme in the future.

Laser Gyros

Another method, which is very interesting for the same application and will be available in the near future, is described in the following. It is the laser gyro technique /4/.
Here we have to discriminate between two different principles:

- The Ring Laser technique, which has achieved already the status of operational use. Aircrafts like Airbus A310, Boeing 767 and 757 make use of it. The basic concept is shown in fig. 5.
- The Fiber Optic Gyro System (FIGS), which uses also a laser signal source, but applies optical fibers for guiding of the light. This technique is shown as a concept in fig. 6.

The Ring Laser, although in its performance excellent, is still an expensive instrument. It is, therefore, not discussed in the following, although there are developments going on to overcome this problem. It is rather the optical fiber laser, which I think, should be looked at here. It is, in combination with a GPS receiver, a promising device for the photogrammetry /5/ to /8/. Several systems of this type will be available commercially in the near future. They will be very robust, consisting of the fibers and of integrated electronic and integrated optical circuits only. It lends itself, therefore, to automatic mass production and allows to adjust the layout to its performance needs. The more accuracy and sensitivity is required the longer the optical fibers must be chosen. The size of the gyro-unit is about a cigar box. With three such units strapped on the camera one could determine the three angles of rotation.
It might be too premature to give already some numbers for the accuracy, which can be achieved under operational conditions. But the Institute for Navigation will test such unit end of this year. We are confident that both, the GPS-receiver technique and the gyro-technique, will become important tools for future photogrammetric tasks.

References

/1/ Bruland, R. V. (1981): Integrated Air Survey Navigation, Photogrammetric Week, Stuttgart

/2/ Grimm, A., Heimes, F.-J. (1984): CPNS Computer-Controlled Photo Navigation System for Special Missions, Operations Symposium '84, Nürnberg

/3/ Heimes, F.-J. (1985): Precision Aircraft Guidance in Antarctica, Photogrammetric Week, Stuttgart

/4/ Hursh, J. W. (1985) A Laser-Inertial Airborne Surveying System, Symposium "Gyro Technology 1985", Stuttgart

/5/ Young, W. A., Bednarz, B. et al. (1985): Closed Loop Heterodyned Fiber Optic Gyroscope, Symposium "Gyro Technology 1985", Stuttgart

/6/ Kiesek, E., Baron, K. U. (1985): Miniaturized All-Fiber Gyro with Novel Signal Detection Scheme, Symposium "Gyro Technology 1985", Stuttgart

/7/ Auch, W., Rahlfs, D. (1985): Fiber Optic Gyro System Applications on Strapdown Attitude Control, Symposium "Gyro Technology 1985", Stuttgart

/8/ Giles, I. P., Mackintosh, J., Culshaw, B. (1985): Optical Fiber Gyroscope in High Performance System, Symposium "Gyro Technology 1985", Stuttgart

Summary

The use of auxiliary navigational data for the photogrammetric corrections may reduce considerable the workload in aerial photography. Auxiliary data are mainly the three-dimensional vectors of position and attitude of the aircraft and, more precisely, of the camera. These data are also very important for remote sensing by means of imaging scanning devices and for laser and microwave profiling.
This paper deals mainly with two methods, providing auxiliary data:

- The GPS-receiver technique, which is, in principle, able to deliver both, position and attitude information, and
- The fiber optic rotation sensor, which seems to become an interesting attitude control instrument, robust, small and reasonable in price.

Photogrammetrische Woche 1985
Institut für Photogrammetrie
Schriftenreihe, Heft 11, 1986

NEUERE MÖGLICHKEITEN DER BILDFLUGNAVIGATION

Zusammenfassung

Die Verwendung der sog. Hilfsdaten der Navigation für die Aufgaben der photogrammetrischen Korrekturen kann möglicherweise den Arbeitsaufwand bei der Luftbild-Photogrammetrie erheblich reduzieren. Hilfsdaten sind vor allem die dreidimensionalen Vektoren der Position und der Lage des Flugzeugs bzw. der Kamera. Diese Daten sind auch für abbildende Scansysteme sowie für Laser- und Mikrowellen-Profiler bedeutsam.
Es werden zwei Methoden vorgestellt, die entsprechende Hilfsdaten liefern können:

- Die GPS-Empfängertechnik, die im Prinzip die Möglichkeit bietet, sowohl die Position als auch die Orientierung zu bestimmen und
- die Laser-Kreiseltechnik, die eine interessante Methode zur Lagekontrolle bietet und sich in robuster Form als kompaktes Instrument für relativ niedrige Kosten realisieren läßt.

Prof. Dr.-Ing. Ph. Hartl
Institut für Navigation
Universität Stuttgart
Keplerstr. 11
D-7000 Stuttgart 1

Photogrammetrische Woche 1985
Institut für Photogrammetrie
Schriftenreihe, Heft 11, 1986

	frequency	length of one element time/range	resolution within one element	possible range resolution
C/A-code	1 kHz	1 msec = 300 km	1 chip	300 m
P -code	1/7·86400 Hz	1 week	1 chip	30 m
C/A-chip	1.023 MHz	1/1.023 μs = 293.3 m	< 1/50	< 6 m
P -chip	10.23 MHz	1/10.23μs = 29.3 m	< 1/50	< 0.6 m
L_1-carrier	1575.42 MHz	1/1.57542ns = 19.05cm	< 6° = 1/60	< 0.3 cm
L_2-carrier	1227.6 MHz	1/1.2276 ns = 24.43cm	< 6° = 1/60	< 0.4 cm

Table 1: Ranging information from GPS-signals

Error Source	Absolute	G/A Receiver	P Receiver	Difference GPS
Ephemeries	3.5m	same	same	0 -1m f(base)
Satellite	1.5m bias	same	same	0 -1m f(base)
clock	0.7m rand	same	same	0 -0.7m
ionosphere	4 m	4m	4 cm	0 -1m (C/A)
troposphere	0.5m	same	4cm modelling	
multipath		1m-0m	1m-0m	1m-0m
receiver		6m-1m	6m-0m	dm-om

Table 2: GPS Error Budget

Scale	h/m	sigma/m x or y	sigma/m z	angle/rad pitch,roll	angle/rad yaw
1:4.000	600	0,02	0,06	1x10exp-5	3x10exp-5
1:10.000	4500	0.5-1	0.5	1x10exp-4	1x10exp-4
1:50.000	6500	2.5-5	1-2	3x10exp-4	3x10exp-4

Tab. 3: Photogrammetric requirements on position and attitude accuracy in orders of magnitude (private communication with F.Ackermann)

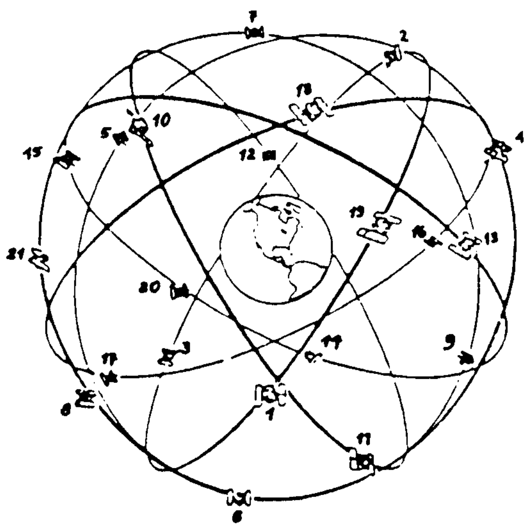


Fig. 1: NAVSTAR Operational Constellation
18 Satellites and 3 Active Spares

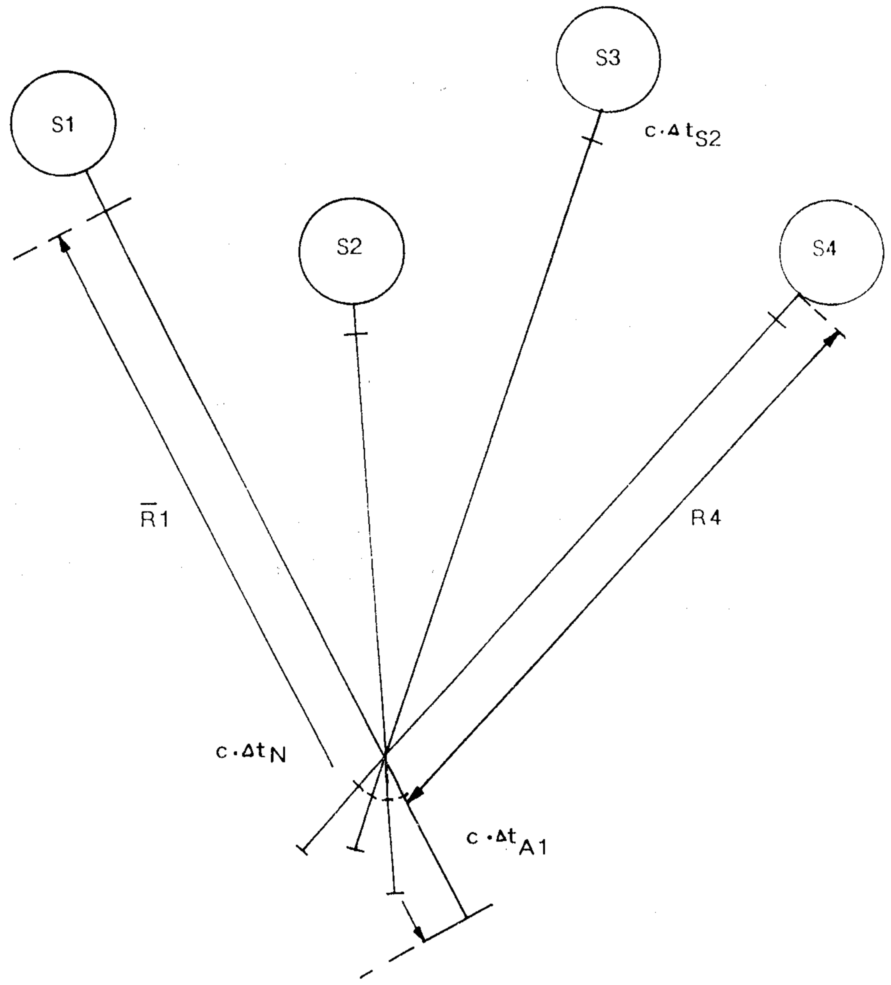


Fig. 2: Pseudo-Range

$$\bar{R}_i = R_i + c\Delta t_{Ai} + c(\Delta t_N - \Delta t_{Si})$$

R_i = true range
t_{Si} = satellite time offset
t_N = receiver time offset
t_{Ai} = propagation delay
c = velocity of light

The satellite GPS-time offset of 4 satellites leads to 4 equations:

$$(X_1-X_N)^2 + (Y_1-Y_N)^2 + (Z_1-Z_N)^2 = (R_1-B)^2$$
$$(X_2-X_N)^2 + (Y_2-Y_N)^2 + (Z_2-Z_N)^2 = (R_2-B)^2$$
$$(X_3-X_N)^2 + (Y_3-Y_N)^2 + (Z_3-Z_N)^2 = (R_3-B)^2$$
$$(X_4-X_N)^2 + (Y_4-Y_N)^2 + (Z_4-Z_N)^2 = (R_4-B)^2$$

the solution of which results in the receiver coordinates X_N, Y_N, Z_N and the Bias B.

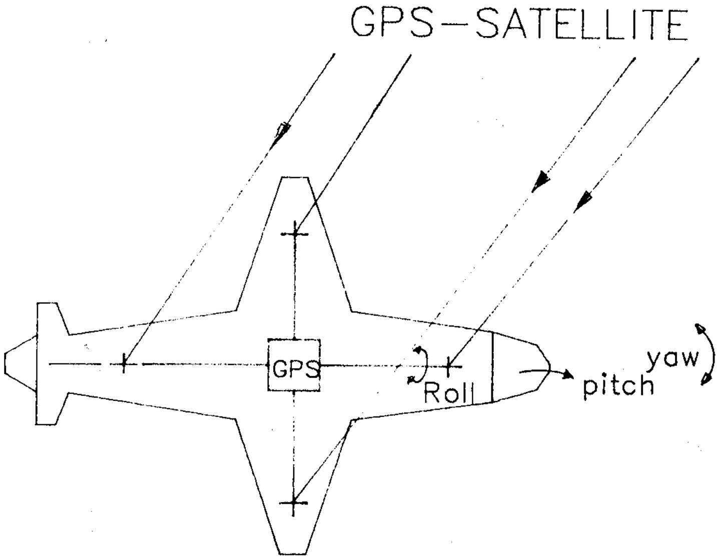
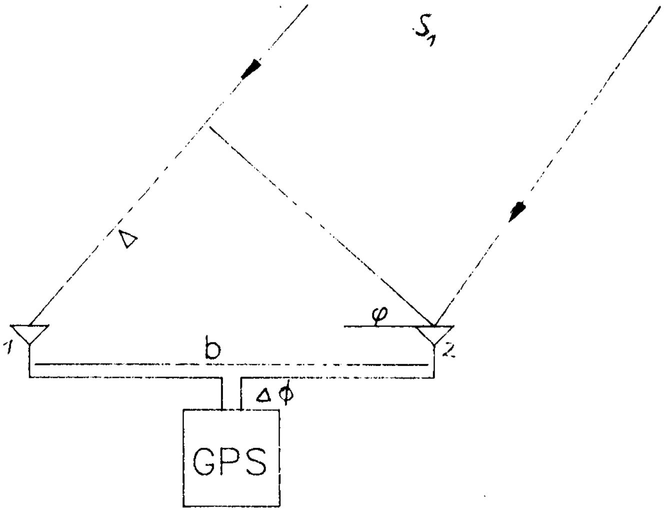


Fig. 3: Attitude control by GPS



$$\Delta = b \sin\varphi$$

$$\Delta\Phi = \frac{2\pi\Delta}{\lambda}$$

Fig. 4: Interferometric Principle

Photogrammetrische Woche 1985
Institut für Photogrammetrie
Schriftenreihe, Heft 11, 1986

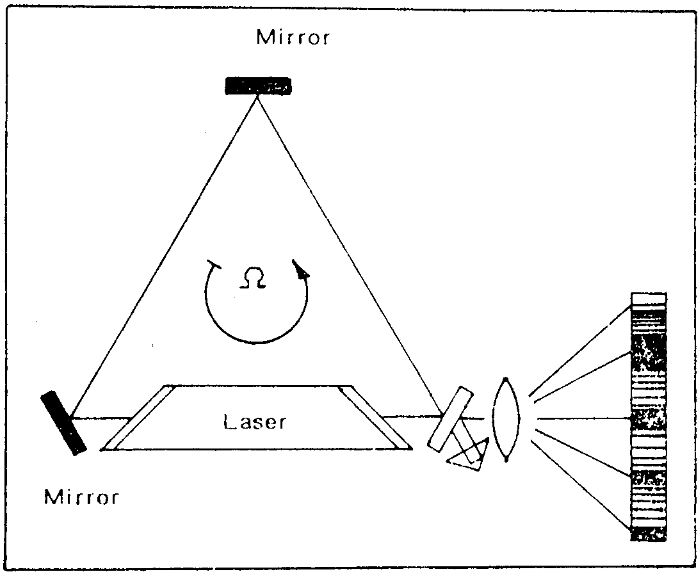
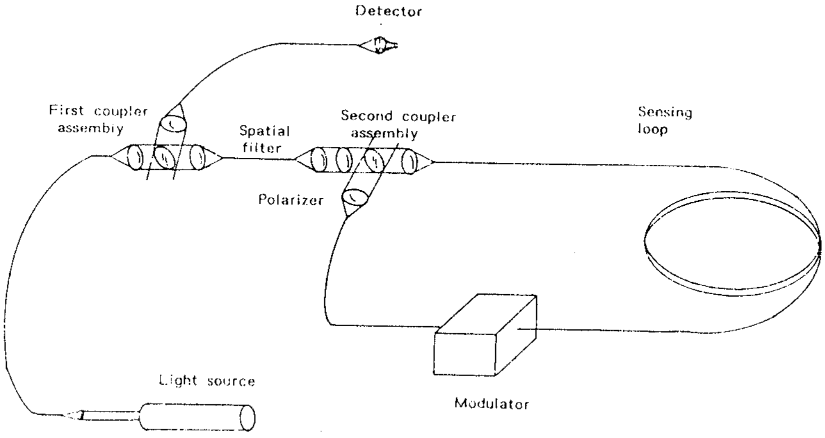
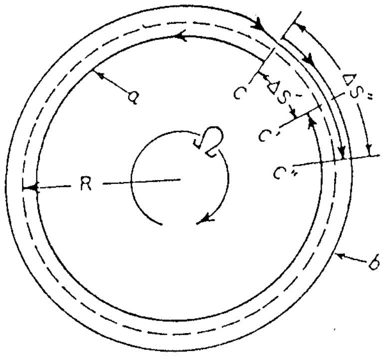


Fig. 5: Concept of the Ring Laser





$$\Delta\tau' = \frac{2\pi R - \Delta S'}{c}$$

$$\Delta\tau'' = \frac{2\pi R + \Delta S''}{c}$$

$$\Delta\tau = \tau'' - \tau'$$

$$\Delta\tau = \frac{4\pi R^2 \Omega}{c^2 - (\Omega R)^2}$$

$$\Omega R \ll C : \quad \Delta\tau = \frac{4\pi R^2 \Omega}{c^2}$$

STATE OF THE ART :

1°/hr to 100°/hr

FRINGE SHIFT

$$\Delta Z = \frac{4\pi R^2}{c\lambda_0}$$

πR^2 =A=ENCLOSED AREA

c=LIGHT VELOCITY

τ=PROPAGATION TIME

Ω=ANGULAR RATE

Fig. 6: Basic Principle and Measurement Concept of the fiber optic laser