Optoelectrical Method of Measuring the Aircraft Track Velocity Vector

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Abstract

This article deals with new principal and basic algorithm of the optoelectronics measuring method of aircraft track velocity vector using digital processing of video signals of CCD line sensors.

1. Principle of the method

During a flight in a constant altitude h the airborne velocity vector is not identical with the vector of the velocity which is corresponding to the pull power of its motors by the influence of an air masses motion. A sufficiently precise determining of track velocity vector components v_{Tx}, v_{Ty}, is a necessary part of an air navigation. These and next terms of an air navigation region (e.g. a course angle α_C, a track angle α_T) are shown in Fig.1.

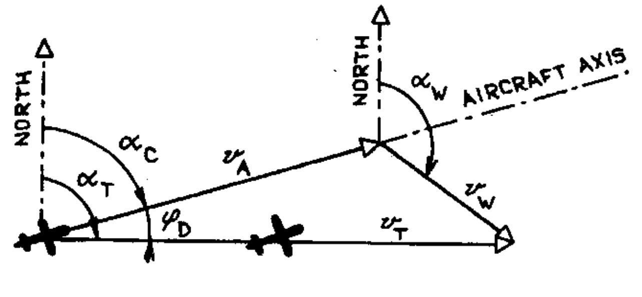

Fig.1 Navigatory triangle of velocities

Modern aircrafts use for a running solution of navigation taskes powerfull board computers. Several measuring methods are used to determine the track velocity and the deviation angle, but they provide not a reasonable accuracy and require relatively complicated technical means. Very valuable autonomous measuring methods do not require any collaboration with an active surface station.

The vertical optical projection of the scanned earth surface into an image plane of two sensors CCD is shown in Fig.2. In Fig.2 means h the altitude of sensors and F_0 the focus length of an used objectiv. It is obvious from the projection that for components h and F_0 of the so-called focus velocity of changes in the brightness function it holds

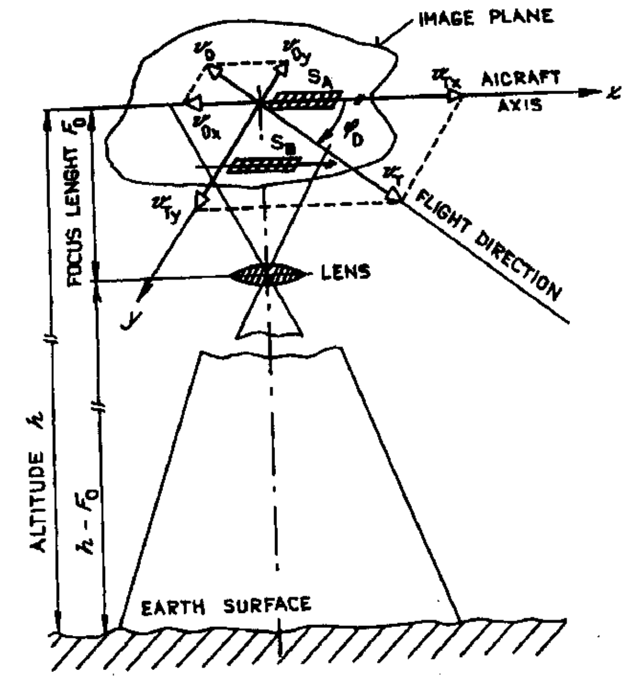

Fig.2 Optical projection of the brightness function B(x, y, t) coresponding to the earth surface into the image plane of two sensors S_a and S_b

$$v_{0x} = -\frac{F_0}{h} v_{Tx} \tag{1}$$

$$v_{0y} = -\frac{F_0}{h} v_{Ty} \, . \tag{2}$$

The method, proposed at the Department of Radioelectronics, Faculty of Electrical Engineering, Technical University of BRNO, used a reality that these component velocities are possible to be calculated on a basis of an analysis of digitalized video-signals of two double CCD sensors S_a, S_b (or by means of a part of an image sensor CCD), scanning in a defined short time interval two other parts of the earth surface. The component velocities v_{Tx} and v_{Ty} are then possible to be expressed from the equations (1) and (2). For the track velocity v_T and the deviation angle φ_D it holds

$$v_T = \sqrt{v_{Tx}^2 + v_{Ty}^2} = \frac{h}{F_0}\sqrt{v_{0x}^2 + v_{0y}^2} \tag{3}$$

and

$$\varphi_D = arctg\frac{v_{Ty}}{v_{Tx}} = arctg\frac{v_{0y}}{v_{0x}} \, . \tag{4}$$

Changes in the altitude h during a flight must be corrected by data of a board altimeter.

For total time derivatives of a two-dimensional brightness function $B(x,y,t)$, projected into the image plane of sensors in perpendicular axis, it is possible to write

$$\frac{dB(x,y,t)}{dt} = \frac{\partial B(x,y,t)}{\partial x}\frac{dx}{dt} + \frac{\partial B(x,y,t)}{\partial y}\frac{dy}{dt} =$$

$$= \frac{\partial B(x,y,t)}{\partial y} v_{0x} + \frac{\partial B(x,y,t)}{\partial y} v_{0y} \tag{5}$$

Both sensors form video signals $U_A(x,y)$ and $U_B(x,y)$ which are proportional in a constant integration time to the brightness of two various parts of the scanning surface, but both ones move with the same velocity. Thus

$$\frac{dU_A(x,y,t)}{dt} = \frac{\partial U_A(x,y,t)}{\partial x} v_{0x} + \frac{\partial U_A(x,y,t)}{\partial y} v_{0y} \tag{6}$$

and

$$\frac{dU_B(x,y,t)}{dt} = \frac{\partial U_B(x,y,t)}{\partial x} v_{0x} + \frac{\partial U_B(x,y,t)}{\partial y} v_{0y}. \tag{7}$$

Equations (6) and (7) are valid for continuous signals. The CCD sensors generate the patterned in time video signal, corresponding to the structure of the light-sensitive layer and to a gradual shifting of accumulated charges to the sensor output. In the case of the double CCD sensors that contains two parallel light-sensitive layers, two patterned in time one-dimensional signals U_{A1}, U_{A2} (or U_{B1}, U_{B2}), which substitute two-dimensional signals $U_A(x,y,t)$, $U_B(x,y,t)$ in equations (6) and (7), are being formed on two outputs. Therefore it's necessary to substitute the differential equations by the difference equations. If we introduce substitutions

$$A = \frac{dU_A}{dt}\ , \tag{8a}$$

$$B = \frac{dU_a}{dx}\ , \tag{8b}$$

$$C = \frac{dU_A}{dy}\ , \tag{8c}$$

$$R = \frac{dU_B}{dt}\ , \tag{8d}$$

$$S = \frac{dU_B}{dx}\ , \tag{8e}$$

$$T = \frac{dU_B}{dy}\ , \tag{8f}$$

it is possible, by a common solution of two independent equations (6) and (7), to express the focus velocity components

$$v_{0x} = \frac{RC - AT}{CS - BT}$$

and

$$v'_{0y} = \frac{SA - BR}{CS - BT} \tag{9}$$

2. Calculation of the direction and time derivatives.

So called measuring point is a basic element for a calculation of one time -and two direction derivatives. The measuring point is an arbitrary geometrical order of sensor video points that makes the possibility to calculate time -and two other direction derivatives (see Fig.3). A position of the measuring point in a space is quite arbitrary. It's neccessary to know an angle between the measuring point and the axis of a plane or any other co-ordinate (precisely the turning of the co-ordinates for what the direction derivatives are in the measuring point calculated). It is possible - with help of one time - and two direction derivatives in two other measuring points after attaining to a system of the equations (6) and (7) to calculate the focus velocity components in two directions. These ones are then possible to recount to the perpendicular coordinates x and y with help of a simple geometrical transformation.

It is neccessary to express the time and direction derivatives A till T by means of the signal samples differences. In the simplest case it's possible to express the derivatives for the measuring point from Fig.3a by following relations

$$\frac{dU_A}{dt} \approx \frac{U_{A1}(n+1,m) - U_{A1}(n,m)}{t_i}\ , \tag{10a}$$

$$\frac{dU_B}{dt} \approx \frac{U_{B1}(n+1,m) - U_{B1}(n,m)}{t_i}\ , \tag{10b}$$

$$\frac{\partial U_A}{\partial x} \approx \frac{U_{A1}(n,m+1) - U_{A1}(n,m)}{d_e}\ , \tag{11a}$$

$$\frac{\partial U_B}{\partial x} \approx \frac{U_{B1}(n,m+1) - U_{B1}(n,m)}{d_e}\ , \tag{11b}$$

$$\frac{\partial U_A}{\partial y} \approx \frac{U_{A2}(n,m) - U_{A1}(n,m)}{d_e}\ , \tag{12a}$$

$$\frac{\partial U_B}{\partial y} \approx \frac{U_{B2}(n,m) - U_{B1}(n,m)}{d_e}\ . \tag{12b}$$

In these relations and in Fig.3

n ... is the serial number of the integrating cycle ($n = 1, 2, \dots, N$);

m ... is the serial number of the sensor pixel ($m = 1, 2, \dots, M$);

t_i ... the integration cycle time (the time of charge accumulation in sensor pixels);

d_e ... the magnitude of the pixel. It is assumed the quarter format and the same distance in the longitudinal or transverse direction;

$U_{A1}(n,m)$, $U_{B1}(n,m)$ ... video signal samples of the first outputs of the sensors S_A and S_B corresponding to the lighting of m-th pixel in the n-th integration cycle;

$U_{A2}(n,m)$, $U_{B2}(n,m)$ ... video signal samples of the

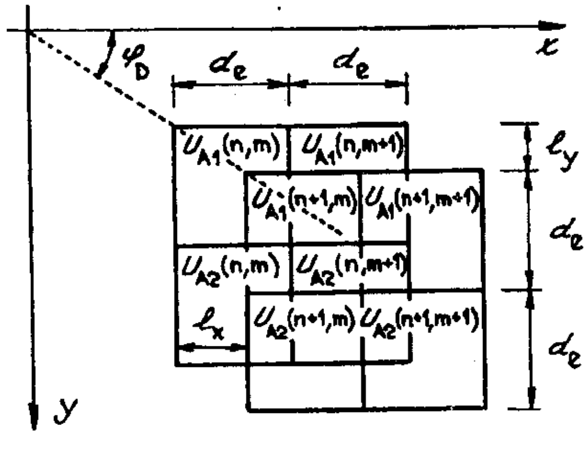

Fig.3a Illustration of the measuring points without turning

second outputs of the sensors S_A and S_B corresponding with the lighting of m-th pixel in the n-th integration cycle.

Relations (10) till (12) were used to calculation the track velocity vector components in a computer simulation of the method. Its results certified that a constelation of the measuring point from Fig.3 is not advantageous.

The method namely provides in this case the most precise results only if the velocity v_{0x} corresponds to the shift $l_x \approx d_e$ and $l_y \approx d_e$ (or v_{0y} corresponds to $l_y \approx d_e$ and $l_x \approx d_e$). In real values of the deviation angle (from -20 to +20 deg) the relative error e_x of the focus velocity in the direction x will be much smaller than the relative error e_y. The focus velocity component v_{0x} is namely much bigger then the component v_{0y}, and therefore the correlation between the values of the brightness distribution function, for what the time derivative and the derivative in the direction x are calculated ($U_{A1}(n+1,m)$, $U_{A1}(n,m+1)$), is much bigger than the correlation between the points ($U_{A1}(n+1,m)$, $U_{A2}(n,m)$), from whose the time derivative and the derivative in the direction are calculated (the same is valid for sensor S_B). For an increasing of the result accuracy it is necessary that the relative errors e_x, e_y of the focus velocity components calculation will be in both directions approximately the same. The value of the time derivative it's consequently necessary to determine in such points of the brightness distribution function, in what the correlation with the points of measuring both direction derivatives is the best. The measuring of two direction derivatives must not be running in the perpendicular directions.

That's why it seems to be advantageous to change the point of the determining the derivative in the direction. Assume the same position of the measuring point as in the Fig.3a . The relations for the calculating the time derivative and the derivative in direction will be formally the same ((10), (11)). If the derivative in direction will be calculated by means of relation

$$\frac{\partial U_A}{\partial y} \approx \frac{U_{A2}(n;m+1) - U_{A1}(n,m+1)}{d_e}$$

$$\frac{\partial U_B}{\partial y} \approx \frac{U_{B2}(n,m+1) - U_{B1}(n,m+1)}{d_e} \tag{13}$$

the place of the determining of this direction derivative

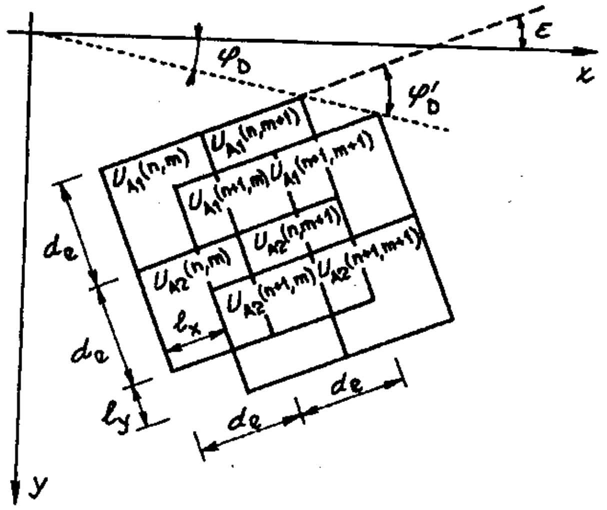

Fig.3b Illustration of the measuring points with turning

would be stereometrically transformed from the point with the value $U_{A2}(n,m)$ to the point with value $U_{A2}(n+1,m)$, which corelation with the place of the determining the time derivative $U_{A1}(n,m+1)$ is for assumed deviation angles bigger than if we use the relations (10) till (12) (again the same is valid for sensor S_B).

The disadvantage of this order is that the measuring accuracy is not the same for positive and negative deviation angles. The geometrical order which is showed in Fig.3b eliminates the differencies among errors of measuring the positive or negative deviation angles.

It is achieved by the turning of the measuring point about the angle ε in the direction of negative deviation angles. The direction and time derivatives are calculated according to the relations (10) till (12) (or 13). It's possible to calculate, by means of relations (9), the components of the focus velocity in the direction of a sensor axis v'_{0x} and in the direction which is towards one perpendicular v'_{0y}. Then it is necessary to determine the value of the track velocity vector v'_T and the deviation angle φ'_D by means of (3) and (4). It is then possible to transform these values into the direction of a course axis of the plane by means of the relations

$$\varphi_D = \varphi'_D - \varepsilon \tag{14}$$

and

$$v_T = \frac{\sin\varphi_D}{\sin\varphi'_D} v'_T \tag{15}$$

3. Track velocity vector components calculation.

After determination the time and direction derivatives for $n = 1, 2, \dots, N$ and $m = 1, 2, \dots, M$ from relations (9) the components of the focus velocities v_{0xi} and v_{0yi} are subsequently calculated. For N integration cycles and M

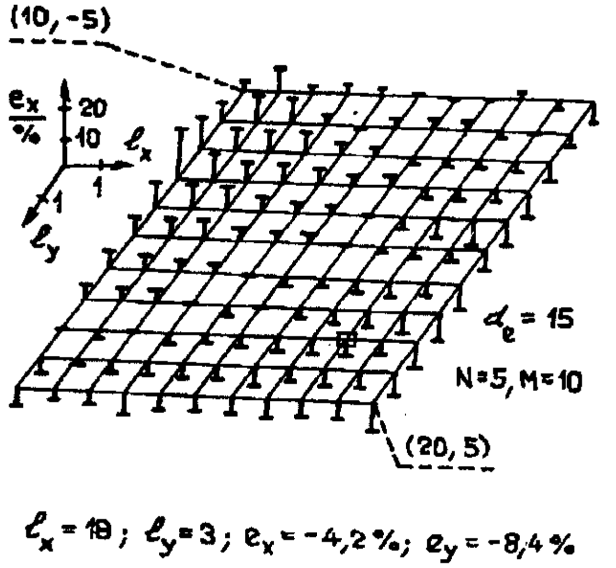

Fig.4a Graphic illustration of the relative errors of the track velocity vector components.

light-sensor points it is possible to obtain a set that contains $(N-1)(M-1)$ values v_{0xi} and v_{0yi}, from which the mean values $\overline{v_{0x}}$ and $\overline{v_{0y}}$ will be calculated in perpendicular coordinates by means of the relations

$$\overline{v_{0x}} = \frac{\sum_{i=1}^{(N-1)(M-1)} v_{0xi}}{(N-1)(M-1)}$$

and

$$\overline{v_{0y}} = \frac{\sum_{i=1}^{(N-1)(M-1)} v_{0yi}}{(N-1)(M-1)} \tag{16}$$

It's possible to determine, in radial coordinates, the mean values of the track velocity v_T and the deviation angle φ_D in a time interval $N\Delta t_i$ from relations (3) and (4). A central processor unit makes these calculations including corrections of the calculated values with respect to the instantaneous altitude h of the aircraft.

The integrating-statistic character of the method together with the effective filtering algorithms for cleaning the set of particular focus velocity components from the boundary values eliminates an influence of disadvantageous distributions of the brightness function of the scanning surface parts to the measuring accuracy (e.g. planes with $B(x, y, t) = const$ or on the contrary the sharp brightness crosses). The numeric errors of the calculation algorithms, which are corresponding to the bit representation of the digitalized video signals, affect also at the reachable accuracy of the measuring (it is assumed an 8-bit representation). The obtained data of the track velocity components vector are conclusive only in case of a straight flight without any inclination (possibly with a constant inclination).

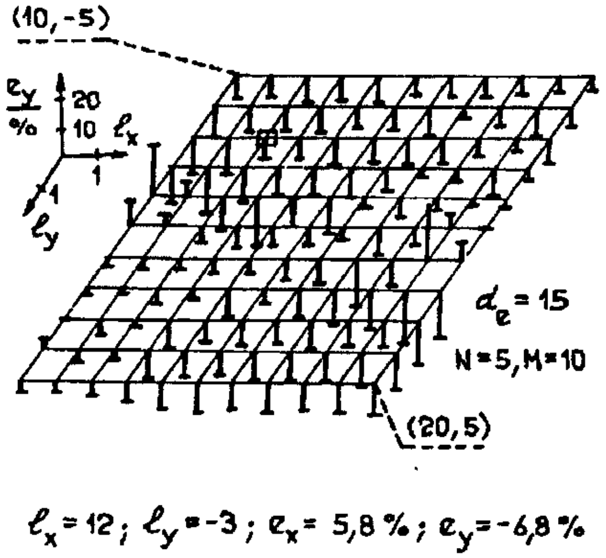

Fig.4b Graphic illustration of the relative errors of the track velocity vector components.

4. Conclusion

Before the beginning of the technical means development, working on the principle of the proposed method, the characteristics of the system have been verified using a computer simulation. It has followed mainly a verifying of an influence of the character of the scanning brightness function (mainly the influence of a spectral components whose wavelengths are similar in comparison with the magnitude d_e of the sensor pixel) to the measuring accuracy; an optimalization of parameters (e.g. a neccesary minimal number of the pixels, a minimal number of the integrating cycles, etc.); a verifying of the algorithms using for a filtering the set of the component focus velocities; an influence of the numerical errors corresponding to the used bit representation of the video data etc. The simulation was practised for some determined or random brightness distributions including digitalized real airborne frames of the earth surface and it made possible to change in a wide interval all of the parameters of the measuring system.

It is impossible, in an extent of this article, to introduce all of reached results. The simulation verified a correctness of theoretical considerations and a vitality of the proposed method. It has proved a correctness of the next stage - the development of the techical means of the measuring system. Relatively low measuring accuracy (to 15%) resulting from the computer simulation of the process of an optoelectronical transformation in the case of the real frames, has probably the continuity with a too rought sampled raster of the digitalized video data (256x256 samples). At present a realization of a digitizer that is making the possibility to digitalize the video models in the raster 800x800x8 bits has been finished at the Department of Radioelectronics, Faculty of Electrical Engineering, Technical University of Brno. This device would make the possibility to an essentially objective justification of the reachable quality of the measuring method (especially the measuring accuracy). Graphic illustration of the relative errors of the track velocity vector components for some values of the track velocity and the deviation angle are introduced in Fig.4 (as an example of a result interpretation).

References

[1] MOSKE,O. and FIRSEKEIN,O.: Airbone ground velocity determination by digital processing of electro-optical line sensor signals. Optical Engineering, 1982, Vol. 21, No2, pp. 370-375

[2] ŘÍČNÝ, V.: The algorithmization of the method of measuring, by light sensitive sensors, the aircraft velocity vector. Modelling, Simulation and Control, B, AMSE Press, Vol. 35, No. 4, 1991, pp,45-51.

[3] ŘÍČNÝ ,V.-MIKULEC,J.: Meření traťové rychlosti a úhlu snosu letadla pomocí řádkových světlocitlivých snímačŮ CCD. Slaboproudý obzor (in press).

[4] MIKULEC,J.: Počítačová simulace optoelektronické metody meření vektoru traťové rychlosti letadel pomocí řádkových světlocitlivých snímačů CCD. Diplomová práce, KREL FE VUT v Brne, 1991, (Diploma work).

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