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METHOD OF GPS SIGNAL FILTRATION FOR ATTITUDE DETERMINATION

The aim of this work was modification of a classical method of attitude determination in the field of processing signal received from satellites, which gives opportunity to reduce interference of electromagnetic wave propagation and measurement errors. This modification improves accuracy and increases dynamics of attitude determination.

METODA FILTRACJI SYGNAŁU GPS W USTALENIU POŁOŻENIA

Celem pracy było opracowanie modyfikacji metody klasycznej wyznaczania orientacji przestrzennej, w obszarze obróbki sygnałów odbieranych z systemu satelitarnego, która umożliwi redukcję zakłóceń związanych z propagacją fali elektromagnetycznej i błędów powstających w procesie pomiarowym, pozwali na poprawę dokładności i zwiększenia dynamiki wyznaczania orientacji przestrzennej.

Wykonana modyfikacja metody klasycznej obejmuje między innymi:

- wykorzystanie komplanarnych wektorów jednostkowych baz (układu antenowego),
- wygładzanie różnic faz sygnału nośnego,
- korekcję macierzy obrotów na podstawie pomiarów poprzedzających.

Efekty jakie uzyskano w proponowanym rozwiązaniu (poprawa dokładności i zwiększenie dynamiki w stosunku do metody klasycznej) pozwalają na pełne zastosowanie metody wyznaczania orientacji przestrzennej, opartej na systemie nawigacji satelitarnej GPS, na statkach powietrznych z możliwością konstruowania układu antenowego w jednej obudowie i wyeliminowanie wpływu drgań anten – które są głównym źródłem błędów – bez konieczności przeciwdziałania tym zakłóceniom.

1. INTRODUCTION

Attitude determination has a wide range of applications in navigation (air, sea and land), AFCSs, robotics, strip mining, drilling platforms and transport. Most of devices for attitude determination are based on inertial systems. New generation of inertial systems is based on optical gyroscopes. These gyroscopes have high sensitivity of 0.1 to 0.001 °/h, but their error strongly depends on the duration of work. According to this characteristic, we need new sources of information on attitude determination, which is independent of time. A method based on satellite systems of navigation like GPS, GLONASS or GALILEO could be a solution.

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2. THE CLASSIC METHOD OF ATTITUDE DETERMINATION

The method based on satellite systems of navigation gives opportunity to attitude determination by taking measurements of differences in signals received by minimum three antennas in specific configuration in space (antennas' structure). Installation of this antennas' structure on board gives information about the attitude determination of the object. The measured difference in carrier phase between two antennas (1) with reference to range between the pair of antennas is proportional to the angle between baseline vector (defined by antennas) and unit vector to satellite (Figure 1).

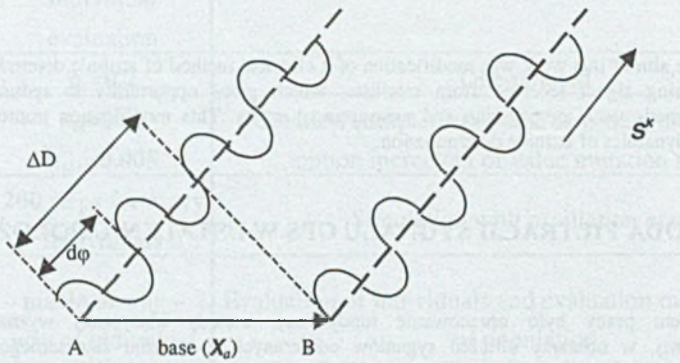

Fig.1. Difference in signal carrier phase between the antennas from one satellite *k*

$$d\varphi_a^k = \boldsymbol{S}_a^{\ k} \boldsymbol{X}_a - N_a^k + \upsilon_a^k \tag{1}$$

Where:

$d\varphi_a^k$ – carrier phase difference between the antennas from one satellite *k*
ΔD_a^k – path difference (differential range) between antennas to satellite *k*
$\boldsymbol{X}_a$ – baseline vector (vector defined by antennas)
$\boldsymbol{S}_a^k$ – line – of – sight unit vector to GPS satellite *k*
N_a^k – integer number accounting for the ambiguity due to limited length of the carrier wavelength
υ_a^k – propagation and measurement errors (bias error, noise)

Knowledge about these angles (from minimum two satellites) allows Euler angles of roll, pitch and yaw to be estimated. Two angles can be given by measurements taken using three antennas and two satellites. Installation of specific receiver and the antennas' structure on board of the object gives opportunity to estimate Euler angles: roll, pitch and yaw of this object. Measurement of carrier phase difference includes errors due to different sources like environment of propagation (ionosphere, troposphere), receiver clock time errors, antennas' structure geometry, vibration of antennas and difference between two distances: geometry distance between antennas and electric distance between antennas.

Accuracy of attitude determination with methods based on the GPS depends also on the satellite configuration used in process of estimating the attitude.

Currently, the process of attitude determination consist in converting differential range measurements based on information about integer number ambiguity N_a^k and differential carrier phase measurement $d\varphi_a^k$ into attitude solution. An optimum attitude solution for a given set of range measurements ΔD_a^k taken at a single epoch for baseline a and satellite k is obtained by minimising the quadratic attitude determination cost function (2) for the m baseline and n satellites:

$$J(A) = \sum_{a=1}^{m}\sum_{k=1}^{n}\left(\Delta D_a^k - X_a^T A S^k\right)^2 \qquad (2)$$

Where:

ΔD_a^k – difference in distance of antennas to satellite k defined with baseline a

m – number of baselines used in process

n – number of satellites used in process

X_a – baseline vector (vector defined by antennas) described in object's co-ordinate system

S^k – line – of – sight unit vector to GPS satellite k described in local-horizon co- ordinate system $S^k = [S_x; S_y; S_z]^T$,

A – matrix of attitude transformation from the local-horizon co-ordinate system to the object co-ordinate system

Present process of attitude determination [3, 4, 5] involves many differential carrier phase measurements achieved by multiple measurements taken in search for solution based on mean values of roll, pitch and yaw angles (Fig.2).

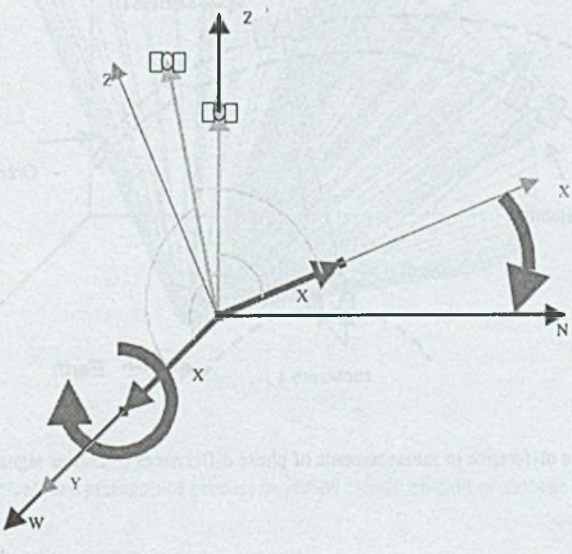

Fig.2. Geometrical interpretation of the process of attitude determination with classic method

What follows is that errors reduction takes place in process of search for mean solution of attitude determination, not during signal processing. For this reason, it seems reasonable to use special signal-processing applications (signal received by antennas from satellites) for reduction and elimination of errors connected witch propagation and measurement errors. This solution can give improvement in accuracy of attitude determination and improvement in dynamics of attitude determination system.

3. MODIFICATION OF THE CLASSIC METHOD OF ATTITUDE DETERMINATION

Currently used methods of attitude determination show poor accuracy with small number of measurements taken, which in consequence to leads to poor dynamics of methods of attitude determination. Reduction in interference and receiver errors due to crosstalk, line bias, interchannel bias gives opportunity to reduce the needed number of measurements in the course of attitude determination (according to accuracy) which, in turn will give opportunity to increase dynamics of the method and widen the range of applications of this system. Proposition of using signal processing entailed radical changes in attitude determination process. Proposition to modify the method is based on using the technique double difference in measurements of phase differences of carrier signal which is used in geodesy for precision range measuring.

Double difference in measurements of phase differences of carrier signal technique allows the following elimination:

- measurement errors
- propagation errors (troposphere, ionosphere)
- receiver errors (electrical range between antennas, clock errors)

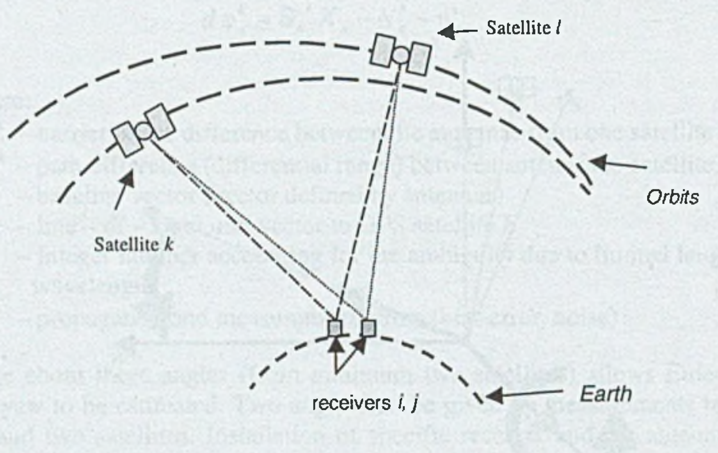

Fig.3. Double difference in measurements of phase differences of carrier signal technique

Errors of object's attitude determination appeared during propagation can be eliminated (Fig.3) on condition that distance between antennas is small (in geodesy: small = less than 1 km), and the signals received by both the antennas experience the same interference in ionosphere and troposphere environments on their way from satellite to receiver.
Furthermore, errors of object's attitude determination depend on the receiver: electrical ranges between antennas, clock errors are the same for signals from both the satellites, which in practice proves always true.
Double difference in measurements of phase differences of carrier signal technique does not reduce signal propagation interference (noise). The proposed modification uses measurement-smoothing technique based on a few pseudo-simultaneous measurements (three or five) followed with averaging them to reduce interference and then accepting a mean value of these measurements in the process of attitude determination.
The mean value of measurements found with the measurement-smoothing technique is calculated step, by step every time from the three or five last measurements. The use of this technique is strongly correlated with the dynamics of the object. This dynamics is inversely proportional to time between measurements and directly proportional to distance between antennas. The proposed modification of the classic method of attitude determination at intermediate stage (Fig. 4) uses co-ordinates of baseline vectors, which gives opportunity to create tentative transformation attitude matrix. This operation is made by means of finding the unit vectors of baselines dislocation, using the formula (3), with account taken of the measurement-smoothing technique.

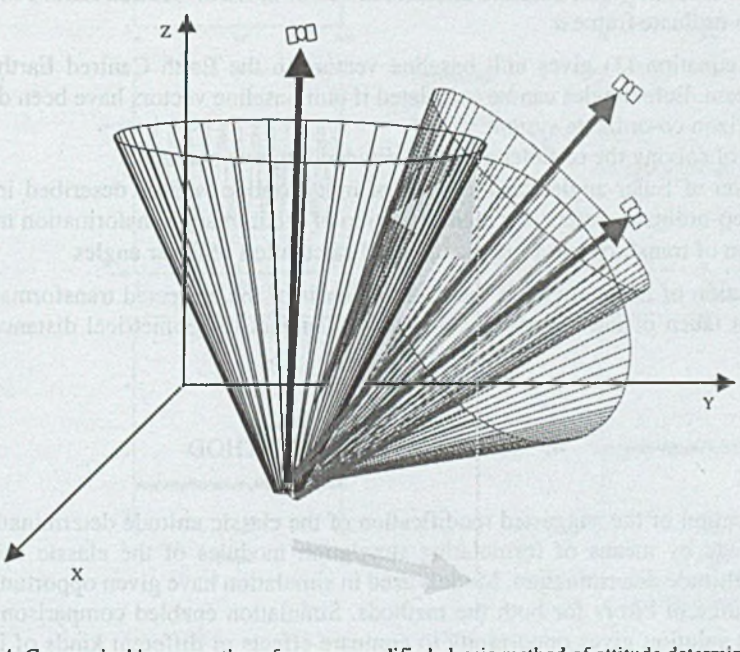

Fig.4. Geometrical interpretation of process modified classic method of attitude determination

$$\begin{bmatrix} WS_x^{12} & WS_y^{12} & WS_z^{12} \\ WS_x^{23} & WS_y^{23} & WS_z^{23} \\ WS_x^{34} & WS_y^{34} & WS_z^{34} \end{bmatrix} \begin{bmatrix} I_{apx} & I_{bpx} & I_{cpx} \\ I_{apy} & I_{bpy} & I_{cpy} \\ I_{apz} & I_{bpz} & I_{cpz} \end{bmatrix} \begin{bmatrix} \|X_a\| & 0 & 0 \\ 0 & \|X_b\| & 0 \\ 0 & 0 & \|X_c\| \end{bmatrix} =$$

$$\begin{bmatrix} W\Phi_a^{12} & W\Phi_b^{12} & W\Phi_c^{12} \\ W\Phi_a^{23} & W\Phi_b^{23} & W\Phi_c^{23} \\ W\Phi_a^{34} & W\Phi_b^{34} & W\Phi_c^{34} \end{bmatrix} - \left\{ \begin{matrix} \begin{bmatrix} WS_x^{12} & WS_y^{12} & WS_z^{12} \\ WS_x^{23} & WS_y^{23} & WS_z^{23} \\ WS_x^{34} & WS_y^{34} & WS_z^{34} \end{bmatrix} \begin{bmatrix} I_{ax} & I_{bx} & I_{cx} \\ I_{ay} & I_{by} & I_{cy} \\ I_{az} & I_{bz} & I_{cz} \end{bmatrix} \begin{bmatrix} \|X_a\| & 0 & 0 \\ 0 & \|X_b\| & 0 \\ 0 & 0 & \|X_c\| \end{bmatrix} + \\ - \begin{bmatrix} N_a^{12} & N_b^{12} & N_b^{12} \\ N_a^{23} & N_b^{23} & N_b^{23} \\ N_a^{34} & N_b^{34} & N_b^{34} \end{bmatrix} + \begin{bmatrix} W\upsilon_a^{12} & W\upsilon_b^{12} & W\upsilon_c^{12} \\ W\upsilon_a^{23} & W\upsilon_b^{23} & W\upsilon_c^{23} \\ W\upsilon_a^{34} & W\upsilon_b^{34} & W\upsilon_c^{34} \end{bmatrix} \end{matrix} \right\} \quad (3)$$

Where:

WS_x^{kl} – difference co-ordinate between smoothed line – of – slight unit vector to GPS satellite k and l

$W\Phi_a^{12}$ – smoothed double difference in measurements of phase differences of carrier signal from two antennas defined baseline a

I_{ay} – co-ordinate y unit baseline vector a in Earth Centred Earth Fixed co-ordinate frame

I_{apx} – co-ordinate y unit baseline dislocation vector in Earth Centred Earth Fixed co-ordinate frame a

Solution of equation (3) gives unit baseline vectors in the Earth Centred Earth Fixed co-ordinate system. Euler angles can be calculated if unit baseline vectors have been described in the local-horizon co-ordinate system.

The process of solving the of Euler angles is divided into two stages:

- calculation of Euler angles on the basis of unit baseline vectors described in the local-horizon co-ordinate system and then definition of preliminary transformation matrix
- correction of transformation matrix and final calculation of Euler angles

Final calculation of Euler angles is made on the basis of the corrected transformation matrix with account taken of the objects rotation vector (subject to geometrical distances between antennas).

4. VERIFICATION OF METHOD

Verification of the suggested modification of the classic attitude determination method has been made by means of formulating simulation modules of the classic and modified methods of attitude determination. Models used in simulation have given opportunity to insert the same source of errors for both the methods. Simulation enabled comparisons of results gained. This solution gives opportunity to compare effects of different kinds of interference and sources of errors upon accuracy and dynamics of the classic and modified methods. For the needs of simulation a model as published in [1, 2] has been assumed, with the simplification assuming circular orbits. This assumption does not degrade simulation because errors of location of the satellite are added to geocentrical co-ordinates (from orbit characteristics).

For simulation purposes it has been assumed that the value of phase difference of carrier signals is equal to the value of difference in distances between satellite and the antennas, multiplied by 360°. When the baseline is longer than the wavelength, it could happen that the wavelength of the signal carrier might appear several times within the distance difference (the problem of ambiguity is covered by [1,2] and therefore has not been discussed in this paper). Two kinds of errors are added to the value of phase difference of carrier signals between the antennas.

- Errors of the measuring system sourced by the receiver, the antenna array's geometry, vibration of the antennas, the receiver's location,
- Propagation errors sourced by the environment of the propagation and the space segment of the satellite system.

The errors needed in simulations can be generated with two methods simultaneously. The first one consists in adding the errors to measurement of the received carrier signal's phase. Values of added errors are found by parameters of these errors described in the literature.

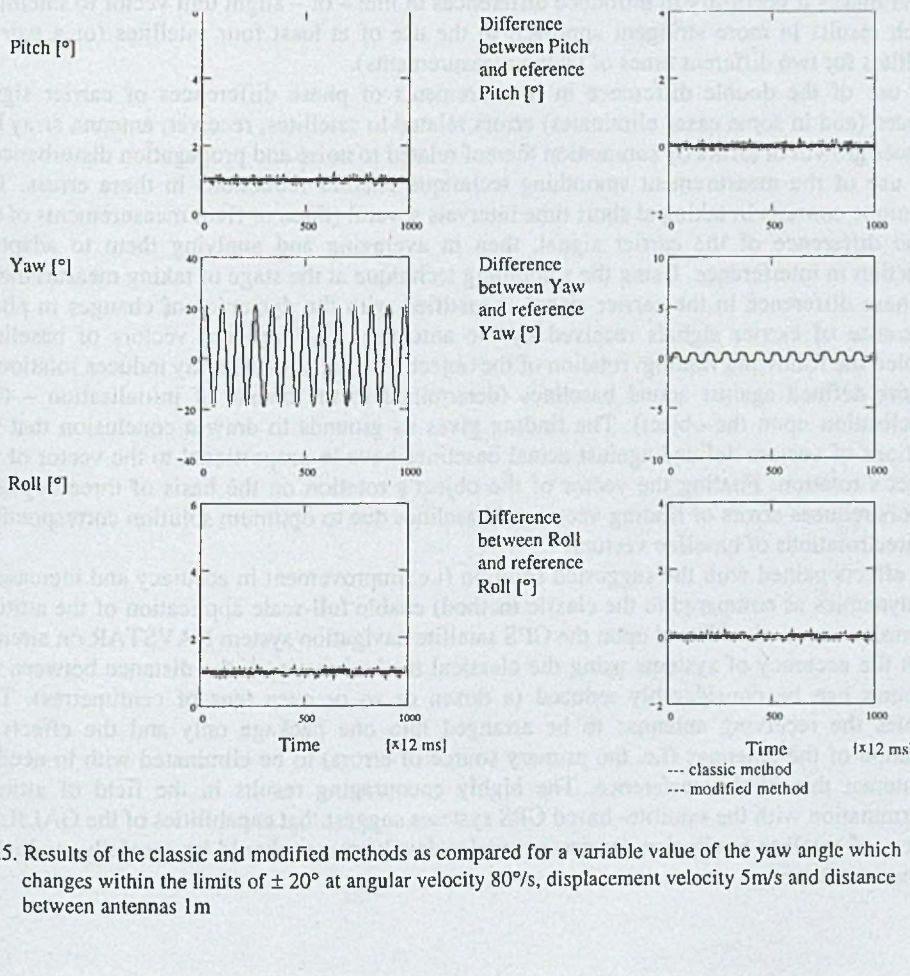

Fig.5. Results of the classic and modified methods as compared for a variable value of the yaw angle which changes within the limits of ± 20° at angular velocity 80°/s, displacement velocity 5m/s and distance between antennas 1m

The second method consists in adding the errors directly to the location of satellites and antennas. Again, for simulation purposes it has been assumed that the errors are of normal distribution [1, 2]. Error-free positions of the antennas have been assumed in the simulation to be data of reference. The standard attitudes found with the models of both the classic and modified methods are referred to the standard attitude (Fig. 5). Such being the approach, there is a chance to draw comparisons between accuracy gained with both the methods for the parameters measured.

5. CONCLUSIONS

The application of coplanar unit vectors has enabled vectors of baselines to be found (within the co-ordinate system that describes positions of the satellites) with the double difference in measurements of phase differences of carrier signal received by the antennas.
The application of the double difference in measurements of phase differences of carrier signal makes it necessary to introduce differences in line – of – slight unit vector to satellites, which results in more stringent approach to the use of at least four satellites (or a pair of satellites for two different times of taking measurements).
The use of the double difference in measurements of phase differences of carrier signal reduces (and in some cases eliminates) errors related to satellites, receiver, antenna array but induces growth of errors by summation thereof related to noise and propagation disturbances. The use of the measurement smoothing technique enables reductions in these errors. The technique consists in taking at short time intervals several (three or five) measurements of the phase difference of the carrier signal, then in averaging and applying them to adaptive reduction in interference. Using the smoothing technique at the stage of taking measurements of phase difference in the carrier signal is justified with the dynamics of changes in phase difference of carrier signals received by the antennas. The coplanar vectors of baselines enabled the following finding: rotation of the object with the antenna array induces rotation of vectors defined against actual baselines (determined in the course of initialisation – first actualisation upon the object). The finding gives us grounds to draw a conclusion that the rotations of vectors defined against actual baselines have to proportional to the vector of the object's rotation. Finding the vector of the object's rotation on the basis of three coplanar vectors reduces errors of finding vectors of baselines due to optimum solution corresponding to three rotations of baseline vectors.
The effects gained with the suggested solution (i.e. improvement in accuracy and increase in the dynamics as compared to the classic method) enable full-scale application of the attitude determination method based upon the GPS satellite navigation system NAVSTAR on aircraft. With the accuracy of systems using the classical method retained, the distance between the antennas can be considerably reduced (a dozen or so or even tens of centimetres). This enables the receiving antennas to be arranged into one package only and the effects of vibration of the antennas (i.e. the primary source of errors) to be eliminated with to need to counteract this kind interference. The highly encouraging results in the field of attitude determination with the satellite- based GPS systems suggest that capabilities of the GALILEO system of satellite navigation (at present under development) should be carefully studied in the nearest future.

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