HYPERBOLIC PASSIVE SURVEILLANCE SYSTEM EFFICIENCY FOR UNMANNED AERIAL VEHICLE SURVEILLANCE IN THE AIRSPACE

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***Abstract* - The importance of Unmanned Aerial Vehicles (UAV) development, production and upgrade in world industrially developed countries has grown since 1980s. UAV control has been transforming from manual control of Unmanned Aircraft (UA) at the range of direct visibility to remote control. Special Unmanned Combat Air Systems (UCAS) arise that consist of UAV adapted for take-off from and landing at Runway or for take off from a starting device, ground control and evaluation station (GCS) and transport vehicles. For navigation and evaluation of reconnaissance information, it is important to have the knowledge of instantaneous coordinates of the UAV position in the airspace and their position displayed on a map-background screen on the desk of ground pilot-operator at GCS. At present, UAV position coordinates are obtained by means of integrated GPS receiver into UAV autopilot system, i.e. an active method. The transmission of positional data information to GCS takes place by radio transmission channel – radio link. The advanced method enabling UAV positional coordinates determination applies Time Difference of Arrival Passive Surveillance System (TDOA PSS), it means independent surveillance of UAV position in the airspace. The purpose of this paper is an analysis of the independent UAV position monitoring method by means of TDOA PSS system and assessing its practical serviceability.**

Keywords: *Data link, Time Difference of Arrival Passive Surveillance System (TDOA PSS), Unmanned Aerial Vehicles (UAV), Unmanned Combat Air Systems (UCAS).*

1. INTRODUCTION

UAV that are impossible to pilot and control within visual contact from the ground are equipped with autopilot. Autopilot maintains UAV airframe stability and its autonomous/no-autonomous navigation during the time of flight. Autopilot serves for securing:

- UAV airframe stability from take-off till landing depending on UAV flight parameters and variable weather and atmospheric conditions.
- Autonomous (according to the programme loaded in advance) or alternatively remote control and navigation of the UAV from GCS.
- Evaluation of the UAV position $P_{(x,y,z)_{UAV}}$ by means of GPS or inertial navigation system (INS).

Fundamental differences between an aircraft autopilot of pilot-controlled aircraft and an autopilot of unmanned aerial vehicle are the following:

- The autopilot of pilot-controlled aircraft serves as a secondary system for airframe stabilization, control and navigation of the aircraft; it means the primary control element of the aircraft is pilot.
- UAV autopilot supports stabilization of the unmanned aircraft airframe by means of flight processor (FP), navigation by means of mission processor (MP) in autonomous flight regime or in remote controlled process by ground pilot-operator from GCS. Successful remote control of UAV by ground pilot-operator consists in based on continuous surveillance of UAV position over ground, it means displaying of the UAV position on the map background screen.

Continuous surveillance about the position of the present existing UAVs is obtained by active method, it means by an onboard GPS/NAVSTAR receiver in 2D alternatively 3D coordinate system. GPS in addition to the discreet flow of positional data $P_{(x,y,z,t)_{UAV}}$ can offer information about ground speed of UAV. Positional data transmission from onboard of the UAV to GCS takes place by a special one-way radio data channel-data link.

Radio data channel-data link integrates independent communication equipment with transmitter on the onboard of the UAV and GPS positional data receiver on GCS. Radio data channel makes use of UHF frequency band; it means propagation of radio waves is straight-line. UAV positional coordinate's measurement error depends on the GPS receiver quality. UAV position measurement error usually is not better than 20m in horizontal plane and 30m in vertical plane. At flight of the UAV in small heights above the ground (which is as a rule) just measurement error of the UAV altitude can cause undesirable collision of the UAV with terrain surface.

For obtaining of the UAV positional data and their subsequently displaying on the ground pilot-operator indicator in the GSC control section TDOA PSS may be used. A new independent method of the UAV position surveillance in the airspace appears. However, the basic problem remains at the theoretical and practical solution

of TDOA PSS efficiency for position determination and surveillance of the UAV in airspace. Theoretical application consists in mathematical analyses of the UAV range-coverage and accuracy of the UAV position measurement depending on TDOA PSS base length. Practical application of the PSS consists in determination of the time period measurement error of electromagnetic waves propagation between UAV in the airspace and TDOA PSS ground receivers, evaluation of the distance differences (hyperbolic system) and no small measure on the construction of an airborne transmitter-beacon and PSS ground equipments.
A block diagram of UCAS electronic accessories and TDOA PSS ground equipments is in Figure 1.

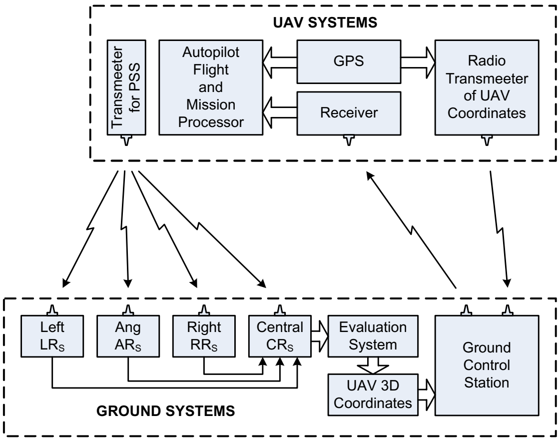

Figure 1 Block diagram of UAS electronic accessories and TDOA PSS equipments for UAV coordinates evaluation.

2. RANGE AND VERY HIGH FREQUENCY POWER REQUIREMENTS FOR THE UAV TRANSMITTER-BEACON

Maximum radius of the radio connection [2] for line-of-sight radio waves propagation is determined by the following equation

$$R_{\max} = 4{,}123\left(\sqrt{h_{A_{GCS}}} + \sqrt{h_{UAV}}\right) \text{ [km;m;m]}, \quad (1)$$

where $h_{A_{GCS}}$ - is the height of receiver antenna above the ground at GCS,

h_{UAV} - is the height of UAV regarding to location of the GCS.

Theoretic technical radius of the radio system is determined by the beacon equation [2]

$$R_{RS} = \sqrt{\frac{P_{T_x} G_{A_{T_x}} G_{A_{R_x}} \lambda^2}{(4\pi)^2 kT_0 FqBL}}, \quad (2)$$

where P_{T_x} - is very high frequency power of the transmitter [W],

G_{T_x} - is the gain of transmitter antenna,

G_{R_x} - is the gain of receiver antenna,

λ - is electromagnetic wave length [m],

k - is Boltzman constant $1{,}37.10^{-23}$ [J/K],

F - is receiver noise factor,

Q - is the signal to noise power ratio at receiver output,

B - is receiver frequency band width [Hz],

L - is losses caused by signal processing and electromagnetic waves propagation in the air.

The relation of the communication channel radius UAV $\Rightarrow$ GCS and height and data channel parameters is in Figure 2.

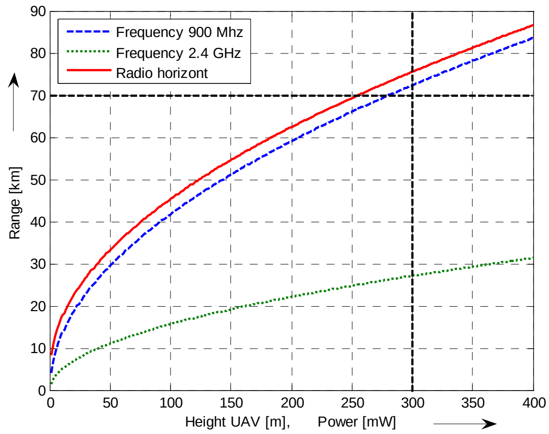

Figure 2:

The maximum radius of a Short Range UAV is within 70 kilometres and within 3000m of maximum altitude. Flight operation of UAV without requested permission from ACC is restricted by maximum altitude 300m. Further, for UAVs to fly at the altitudes above 300m an inevitable condition is to be equipped with the ICAO identification system as applicable [6].
When keeping within these limitations, direct visibility between UAV and the ground receiver antenna (1) is maintained. The UAV onboard transmitter-beacon very high frequency transmitting power requirement is $P_{T_x} \geq$ P=250 mW.
Specified frequency band for data transmission is 900MHz or 2.4 GHz.
From the technical point of view a transmitter-beacon antenna on UAV board is a Quarter-Wave Whip Antenna and the data receiver antenna at GCS can be unidirectional as well as directional with 8dB gain.

3. PLANE (2D) AND SPACE (3D) GEOMETRY OF HYPERBOLIC PSS

For independent surveillance of the UAV position in the airspace there is a possibility to use the TDOA PSS working with the method of the determination of UAV position in the airspace by hyperbolic positional lines (2D) or hyperboloid positional areas (3D). The PSS for military reconnaissance and for ATC use a distance separation between receiver radio stations (base of the system) of tens of kilometres (the base is usually 30km). PSS designed for surveillance of the UAV position in the air space should have the following technical characteristics: distance ***b*** (base) between ground receivers as short as possible, high mobility, time-saving set to operation and high operability [3].

Rightly the base length is the critical parameter of TDOA PSS for surveillance of the UAV position. The base length ***b*** has maximum effect on measurement of UAV coordinates, on the UAV position accuracy, time interval measuring of radio wave propagation from UAV to ground receiver stations to evaluation centre-central receiver station $UAV \Rightarrow L_{R_S} \Rightarrow C_{R_S}$ and on speed of receivers' deployment around GCS.

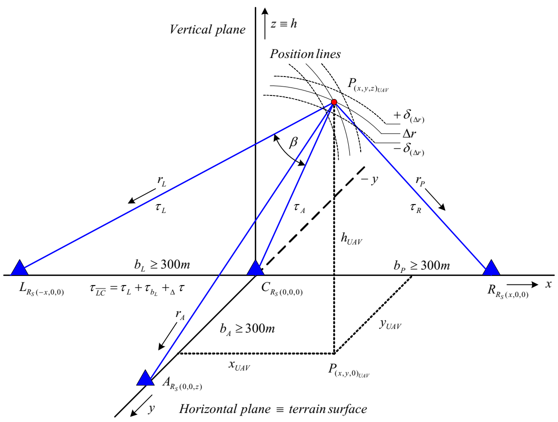

Figure 3: TDOA PSS radio receiver stations lay-out for UAV position determination at 3D system of coordinates

The geometry of hyperbolic surveillance systems creates theoretical foundation of distance difference PSS and have influence on accuracy of UAV coordinate position measurement in the airspace. Radio receivers-stations L_{R_S}, C_{R_S}, P_{R_S} (2D coordinate system), alternatively its augmentation with fourth radio receiver station A_{R_S} (3D coordinate system) form the foci of hyperbolas (hyperboloids). The result is a net of hyperbolic positional lines in the $x \perp y$ plane or of hyperboloids positional areas in airspaces. Distances among $\overline{L_{R_S} C_{R_S}} \equiv b_L$, $\overline{P_{R_S} C_{R_S}} \equiv b_R$ and $\overline{A_{R_S} C_{R_S}} \equiv b_A$ are the bases of 2D TDOA PSS (hyperbolic) or 3D TDOA PSS (hyperboloid) system, see Figure 3, where

L_{R_S} - left side radio receiver,

R_{R_S} - right side radio receiver,

C_{R_S} - central receiver and evaluation station,

A_{R_S} - radio receiver-station for augmentation of 2D PSS to 3D PSS.

Applicable to hyperbolic system TDOA PSS is that the differences of the distances between aircraft and hyperbola foci are constant, it means $\Delta r_{b_L} = r_{L_{UAV}} - r_{C_{UAV}} = k_{b_L}$, $\Delta r_{b_P} = r_{P_{UAV}} - r_{C_{UAV}} = k_{b_P}$ and $\Delta_{b_A} = r_{A_{UAV}} - r_{C_{UAV}} = k_A$. The result of the solution of difference distances in 3D coordinate system is a hyperboloid equation $\frac{x^2}{a_*^2} - \frac{y^2}{b_*^2} - \frac{z^2}{c_*^2} = 1$ turning after substitution for $z = h$ into

$$\frac{x^2}{a_*^2} - \frac{y^2}{b_*^2} - \frac{h^2}{c_*^2} = 1, \tag{3}$$

where

$$a_*^2 = \frac{\Delta r^2}{4}\left[1 + \frac{h^2}{b - \frac{\Delta r^2}{4}}\right] \tag{4}$$

is the length of hyperboloid major axis and

$$b_*^2 = b^2 + h^2 - \frac{\Delta r^2}{4} \tag{5}$$

is the length of hyperboloid minor axes.

The values of the variables a_* and b_* depend on the difference of distance Δr and on aircraft altitude. The hyperbolic net of positional lines made in this way allows to determine the radio signal source-UAV position in 2D TDOA PSS co-ordinate system (three radio posts) or in 3D TDOA PSS co-ordinate system (four radio posts).

The information about TDOA PSS usability in dependence on the base lengths and aircraft altitude results from the distance of particular intersections which is expressed by equation $d = \sqrt{a_*^2 + b_*^2}$. Substituting the equations (4) and (5) into this mathematical equation results into the following equation

$$d = b_* \left\{ \sqrt{1 + \frac{h^2}{b^2 - \frac{\Delta r^2}{4}}} \right\} = b_* \left\{ \sqrt{1 + \frac{\left(\frac{h}{b}\right)^2}{1 - \left(\frac{\Delta r}{2b}\right)^2}} \right\} \quad (6)$$

*The mathematical equation (6) implies that hyperboles foci positions depend on the aircraft-UAV altitude to TDOA PSS base ratio. Consideration of changes of the foci position of positional lines-hyperboles for given UAV altitude **h** is unnecessary or a sufficiently long base of hyperbolic PSS system. Also, the length of the base should be longer than the supposed altitude of the aircraft-UAV, it means $b \geq h$. For UAV altitude lower than 150m the PSS base length of 500 m is sufficient.*

4. ACCURACY OF HYPERBOLIC PSS SYSTEM FOR SURVEILLANCE OF UAV

UAV position measurement error issues from the presumption that there are three positional lines close together: Δr (accurate positional line) and two position lines caused by the error of position measurement $\Delta r \pm \delta(\Delta r)$, where $\pm\delta(\Delta r)$ is the measurement error of the positional line. The vector field of distance difference in the surrounding of the ground radio stations of PSS system may be considered a scalar field of the scalar $\Delta r_{b_L} = r_{L_{UAV}} - r_{C_{UAV}}$. Scalar quantity accruement rate in normal direction of the equipotential surface may be expressed as follows

$$grad(\Delta r) = grad\left(r_{L_{UAV}}\right) - grad\left(r_{C_{UAV}}\right) = = \frac{\partial(\Delta r)}{\partial n}\overrightarrow{n^0} = 2\sin\frac{\beta}{2}\overrightarrow{n^0}, \quad (7)$$

where β - is the angle between radius vectors that connect the UAV P_{UAB} position with radio station posts P_{RS_L} and P_{RS_C}, see Figure 2.

The linear measurement error of the TDOA PSS system is determined by equation

$$\delta = \delta n = \frac{1}{\sin\left(\frac{\beta}{2}\right)}\Delta\tau = \frac{1}{\sin\left[artg\left(\frac{b}{2h}\right)\right]}\Delta\tau, \quad (8)$$

where $\Delta\tau$ - is the error of the measurement of time difference.

The mathematical equation (8) implies that the measurement error of PSS TDOA system depends on base lengths ***b***, on UAV altitude ***h*** and on the system technical ability to measure time values $\Delta\tau$ (see Figure 4). Contemporary time measuring systems allow to measure time with the accuracy better than 10^{-10} seconds.

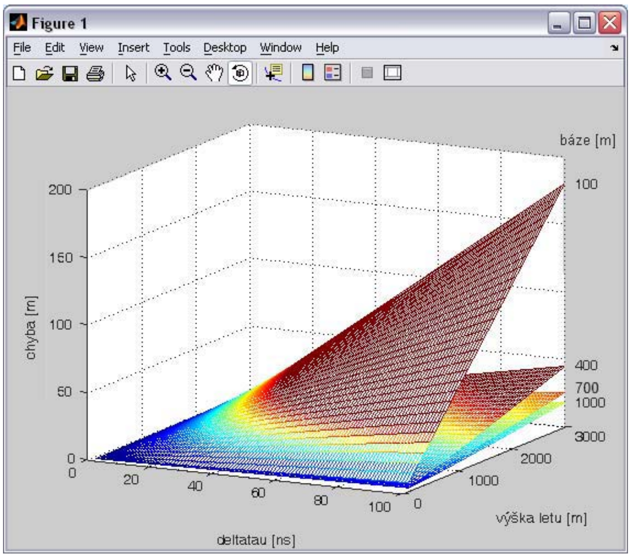

Figure 4:

5. SYSTEM TECHNICAL EQUIPMENT

The availability analysis of current elements shows that onboard transmitter-beacon will probably use a TX_{END} transmitter by MaxStream manufacturer operating in 900MHz frequency band or a 2,4GHz time multiplexer and a half-wave whip antenna.

Identification code section will be designed and produced separately. As the transmitter allows data transmission in time multiplex mode it can be used also for transmission of the positional data obtained by GPS receiver, if need be.

Ground receivers will be from MaxStream too. The antennas of ground radio station receivers will be of half-wave whip type from MaxStream.

The evaluation system will work on personal computer base.

The layout diagram of the ground PSS equipment is in Figure 1.

6. CONCLUSION

The results of the above-mentioned theoretical analysis illustrate that TDOA PSS method is also applicable to UAV position determination and flight trajectory evaluation of the UAV in small altitudes. For time difference measuring among coming radio signals on single PSS ground radio station it is possible to utilize both the radio signal transmitted from GPS positional data transmitter and the signal transmitted by independent transmitter-beacon placed onboard UAV. The later method is more efficient from the viewpoints of both UAV useful load improvement and unique UAV identity determination.

Recently, a computer-controlled simulation of the entire system has been carried out. The results of the simulation confirmed the usability of TDOA PSS system for tracking UAV position on computer display with mapped background and for controlling UAV to follow the planned flight trajectory.

In the next period, PSS system will be verified for practical UAV position tracking.

References

[1] LUZICA, S., SVOBODA, P., GRECMAN, P.: *Mode-S positional data error analysis from the point of view of Air Traffic Control*. Annals of the University of Craiova. Seria: Inginerie Electrica, Anul 30, nr. 30, Romania 2006.

[2] SKOLNIK, M. I.: *Radar handbook - 2nd edition*. McGraw-Hill Book Company. New York 1990.

[3] LUZICA, S., SVOBODA, P., GRECMAN, P.: *Aircraft positional data utilization transmitted by Mode-S at the automated Air Traffic Control Systems*. Academic and Applied Research in Military Science. Volume 6. Issue 2. 2007. Budapest 2007.

[4] LUZICA, S., SVOBODA, P.: *Conditions for air target detection by the help of TDOA PSS*. The 31st Internationally attended Scientific Conference of the Military Technical Academy. Bucharest 2005.

[5] LUZICA, S., SVOBODA, P.: *Perfection and weak places of the TDOA and DF PSS*. 3rd International Conference, Radar & ELINT/ASM Systems, Brno 2005

[6] GRECMAN, P., ANDRLE, M.: *Experience in metering position – GPS/GLONASS*. 7th International Conference on New Development Trends in Aeronautics. Kosice, Slovak Republic 2006.