MODE-S POSITIONAL DATA ERROR ANALYSIS FROM THE POINT OF VIEW OF AIR TRAFFIC CONTROL

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Abstract – **Worldwide spurt growth of the air traffic density concurrently evokes requirements on the continual- increasing of the air traffic control (ATC) quality. Problems of the flight safety will be unquestionably of the major criteria for selection of the technical devices and of the whole flight system organization. It stands to reason, that additional development of the ATC methods and effective use of the airspace is impossible without modernizing of the Communication, Navigation and Surveillance systems jointly with Air Traffic Management (CNS/ATM). One of the real tools for achievement of higher quality of the ATC is utilization of the precise positional information from the onboard segments of the Global Positioning System and Global Navigation Satellite systems (GPS/GNSS) that are transmitted in Mode-S among aircraft and to the ground Area Control Centre (ACC). The papers demonstrate mathematical analyses of different attitudes to the definition of the positional errors measurement, methods and results of experimentally measured data carried in Mode-S in static and dynamic mode.**

Keywords: *Circular Error Probable (CEP), Ellipsoid Error Probable (E3EP), Mode-S, Spherical Error Probable (SEP), squitter.*

1. INTRODUCTION

Fundamental ICAO technical device, for surveillance of the aircraft position in terms of ATC, presents in concurrently time a net of ground Secondary Surveillance Radars (SSR). Among new and very perspective systems of the ATC unquestionably the Global Navigation Satellite System (GNSS) and Automatic Dependent Surveillance-Broadcast (ADS-B) system belong. Although both these new systems have been operationally tested in the long term, but a certain dissension in criteria for evaluation of their real accuracy and safety in operation has persisted so far. It is the result of different definitions and standard specifications, which are used in the world and of the real operation conditions of these systems. Following attitude to analysis of this problem is based on the applied mathematics principles, experimental measurement and on the comparison of the attained results. Expectations of the ATC, inserted into utilization of the positional GPS information in MODE-S have to carry foothold in data reliability in any case of operation. From logic matter is evident; that safeness of the ATC cannot be wholly dependent on one navigation system - universal drugs on problems in general do not usually work according to our expectations. Improvement of the ATC safeness is therefore a major motivation of these papers.

2. MODE-S

MODE-S is a symbol of ICAO for recently established, so called selective interrogation and response mode in terms of ground and airborne within the SSR systems, which work on the carrier frequency 1030 MHz of the ground interrogator and 1090 MHz of the airborne responder.

The MODE-S system solves many of the system problems encountered with SSR Modes A and C. All the necessary data are contained in one reply and the accuracy of the reply data is confirmed by the parity. In contrast, the Mode A and C data are sent separately and have to be correctly associated by the group equipment.

MODE-S uses the 24 bits address [2], which makes it possible to unambiguous worldwide identification within the ATC within the ATC (for the disposal is $N = 2^{24} = 16\ 777\ 216$ individual address) and other bit groups for transmission of different flight parameters into data connection among the aircraft and the ground ATC (Figure 1).

The MODE-S is expected to enable to optimize the air traffic capacity management (OCM), automated support to air traffic services (ASATS), flight data processing (FDP) and airport operations (AO) and improve safety while coping with increased traffic growth.

At the real air traffic conditions unambiguous identification and accurate determination of the aircraft position in the air space including reliable data communication is necessary. However the required accuracy of the aircraft position, obtained by airborne GPS system is not always guaranteed.

The aim of these papers is a positional accuracy analysis; it means theoretical expression of the measurement error and experimental check on the measurement accuracy of 2D and 3D positional data obtained from the MODE-S squitter, what is spontaneously transmitted with period 1 second.

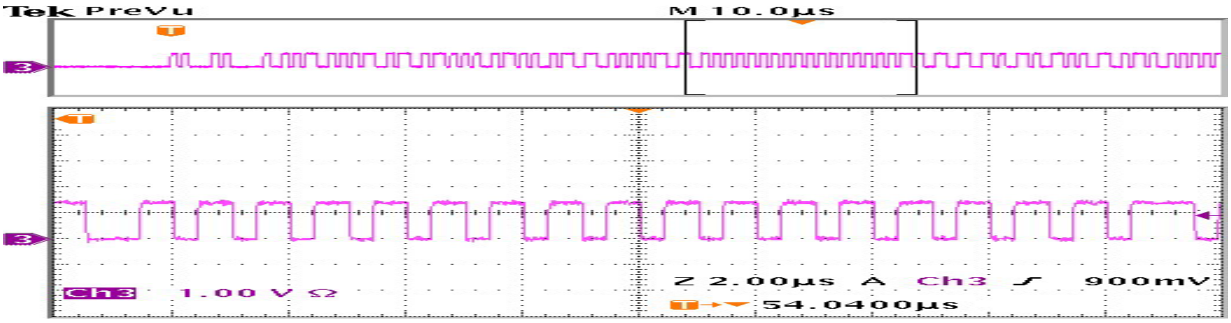

Figure 1: Sample of the real signal in the squitter with positional GPS information in MODE-S

3. POSITION MEASUREMENT ACCURACY

The accuracy of the aircraft position measurement has statistical character and expresses a degree of conformance between the estimated or measured value and the true value.

In accordance with [4] for density distribution error probability in horizontal plain (2D) the following relation holds

$$\varphi(x,y)=\frac{1}{2\pi\,\sigma_x\sigma_y}\exp\left\{-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}\right)\right\} \tag{1}$$

and for the density distribution error probability in space (3D)

$$\varphi(x,y,z)=\frac{1}{\sigma_x\sigma_y\sigma_z\sqrt{8\pi^3}}\exp\left\{-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}+\frac{z^2}{\sigma_z^2}\right)\right\} \tag{2}$$

where $\sigma_x,\sigma_y,\sigma_z$ are the mean square deviations of the measurement.

Ellipsoid errors of equal density probabilities at 3D coordinates (for ellipse errors in 2D coordinates is ***z = 0***) is expressed by the relation

$$\left(\frac{x}{\sigma_x}\right)^2+\left(\frac{y}{\sigma_y}\right)^2+\left(\frac{z}{\sigma_z}\right)^2=t^2$$

or

$$\left(\frac{x}{t\sigma_x}\right)^2+\left(\frac{y}{t\sigma_y}\right)^2+\left(\frac{z}{t\sigma_z}\right)^2=1 \tag{3}$$

where ***t*** is select parameter.

In case of 3D measurement for ***t = 1*** arise so-called central ellipsoid error, whose half-axis are directly equal to the value of the mean square deviations measuring errors. For different values of the parameter ***t*** create a set of co-axial and concentrated ellipsoids with half-axis $a=t\sigma_x, b=t\sigma_y, c=t\sigma_z$, on which all points (errors) are suitable of ellipsoid equation for the particular parameter ***t*** and they have the same probability of appearance, it means they lay on the surface hereof three axis ellipsoid error.

From frequency and summing distribution curve of three dimensional errors in accordance with [1] it is evident, that the error ellipsoid with parameter ***t = 1*** corresponds to the position measurement with probability $\Phi_3(t=1)=19{,}9\,\%$.

The biggest cumulation of three-dimensional errors coming for $t=\sqrt{2}$, where value of the frequency function achieves maximum and corresponding probability determination of the signal source (aircraft) position is equal to $\Phi_3(t=\sqrt{2})=41{,}9\%$.

Measurement position accuracy in the horizontal plain (2D) is possible to express by the Circular Error Probable (CEP) [1] as the circle radius with 50% realization errors

$$\text{CEP} = 1{,}\,18\ \sigma \tag{4}$$

and for space error (3D) measurement as a Spherical Error Probable (SEP) as the globe radius with 50% probability realization errors

$$\text{SEP} = 1{,}\,54\ \sigma \tag{5}$$

Expression of the errors by means of CEP and SEP is relatively easy and practically often used, however it does not express the real error distribution of position measurement.

At the navigation practice the statement of the accuracy in horizontal plain (95%) together with the statement of altitude accuracy (95%) is mostly used.

For description of the error determination in the horizontal plain 2D is also used [6] further formulation such as

$$R(2DRMS)=2\sqrt{\sigma_x^2+\sigma_y^2}$$

or

$$R(DRMS)=\sqrt{\sigma_x^2+\sigma_y^2} \tag{6}$$

These expressions however do not bring uniterming specification of the error definition and from this reason we shall not use them. For positional error analyses and for comparison we shall use CEP, SEP, error ellipse and error ellipsoid.

4. EXPERIMENTAL MEASURING RESULTS

Special workplaces of the University of Defence in Brno and AFRI in Prague performed experimental measuring of the GPS positional errors carried in the signal of MODE-S (Figure 2).

The transmitting part of the workplace (transmitter system) was formed of a MODE-S transmitter of Squitter Beacon - SQB type with HNV-500C Rockwell Collins GPS receiver.

The GPS receiver is obtaining positional information from the GPS system. The transmitter transmits this positional information in Enhanced MODE-S (EMS) DF18 message. We use Extended Squitter/Non Transponder (ES/NT) for experimental purposes. This message contains BDS 06 register (for surface application) or BDS 05 register (for air application).

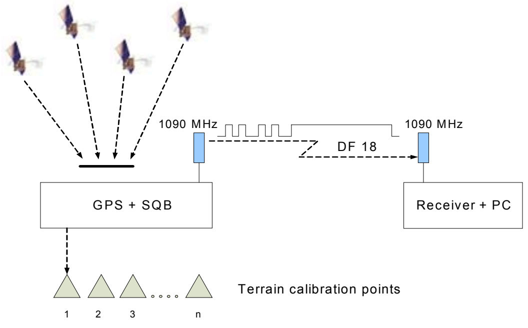

Figure 2: Measuring block diagram

The evaluation part of the workplace (receiver and evaluation system) consisted of a MODE-S signal receiver that worked on the carrier frequency of 1090 MHz, a decoder of MODE-S messages and a PC for positional data processing.

For static measurements, several geodetic points, so called "terrain calibration points" were accurately fixed. The terrain calibration points were fixed in the ETRS-89 reference geographic-coordinate system and from the geographic coordinates (φ, λ, H_{el}) the Cartesian coordinates in the UTM geodetic system (x, y, z) were calculated.

The SQB transmitter was placed on each of these calibration points one at a time, to evaluate position.

Dynamic error was examined with a mobile SQB transmitter and a DGPS check device.

4.1. SQB/Mode-S transmitter positional error in horizontal plane (2D)

From the measured positional data files, transmitted by the SQB from the calibration points [3], the fo mathematical data were calculated with MATLAB software: mean value, mean-root-square errors σ_x, σ_y and error ellipse parameters.

Figures 3, 4, 5 and 6 illustrate the graphic representation of the CEP and E2EP (Ellipse Error Probable) error values.

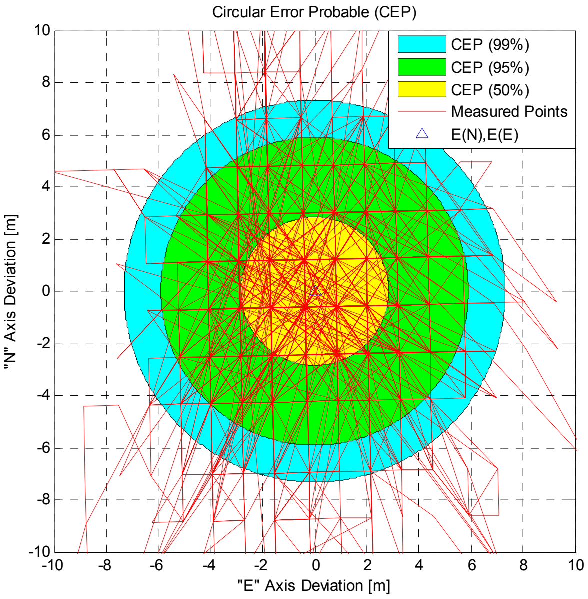

Figure 3: Position error measurement at CEP (with 95% probability) Circle radius $\sigma_{x,y}$ (95%) = 5.9m

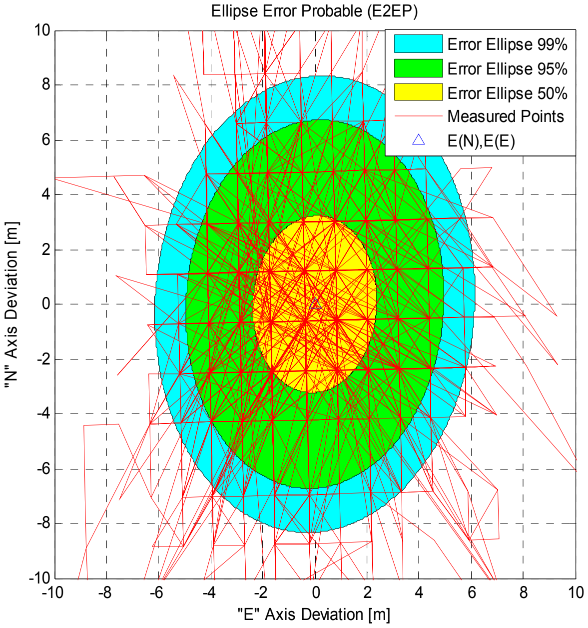

Figure 4: E2EP Error Ellipses (50%, 95%, 99%) Semi-major axis of σ_y (95%) ellipse = 6.73 m Semi-minor axis of σ_x (95%) ellipse = 4.94 m

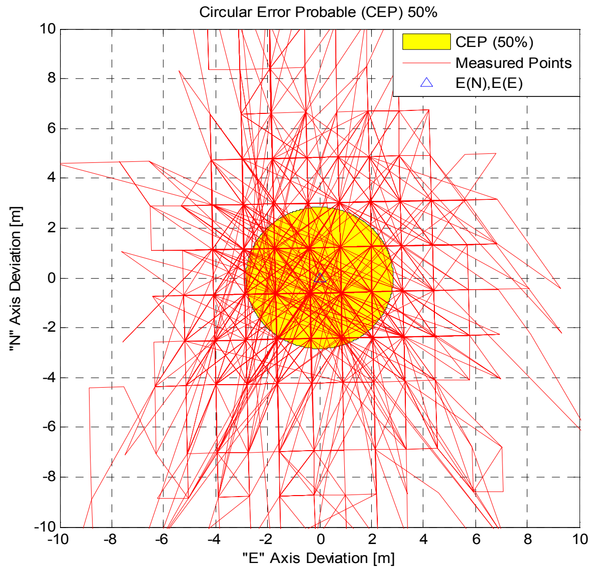

Figure 5: CEP (50%)

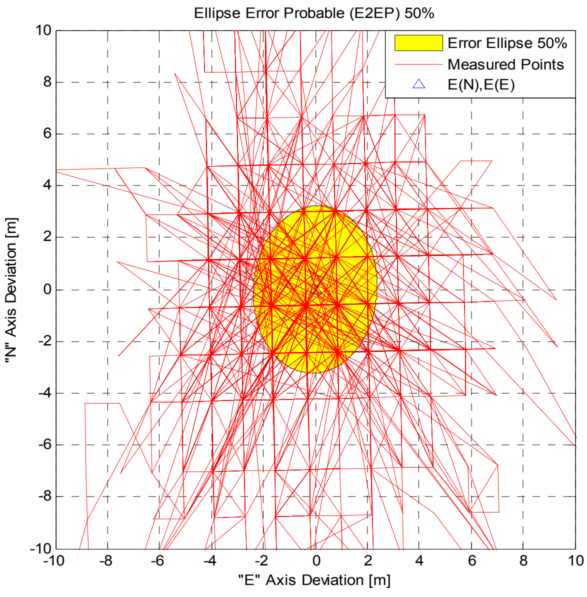

Figure 6: E2EP (50%)

4.2. SQB/Mode-S transmitter positional error in space (3D)

The parameters of the error ellipsoid are defined similar to error ellipse, with an additional altitude coordinate to determine 3D position. The length of each semi-axis of the error ellipsoid on all three axes (x, y, z) is defined by the spatial distribution of the measured points. Position measurement error in space is rendered by error ellipsoid. Figures 7 and 8 show the results of measurement at the same calibration point where in the Fig. 7 is spread of points in the space and in the Fig. 8 is the error ellipsoid of these points for 95% probability.

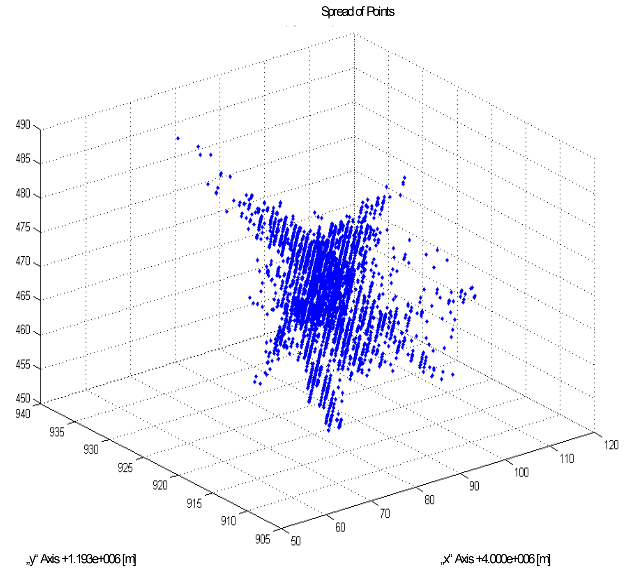

Figure 7: Calibration point position measurement variance

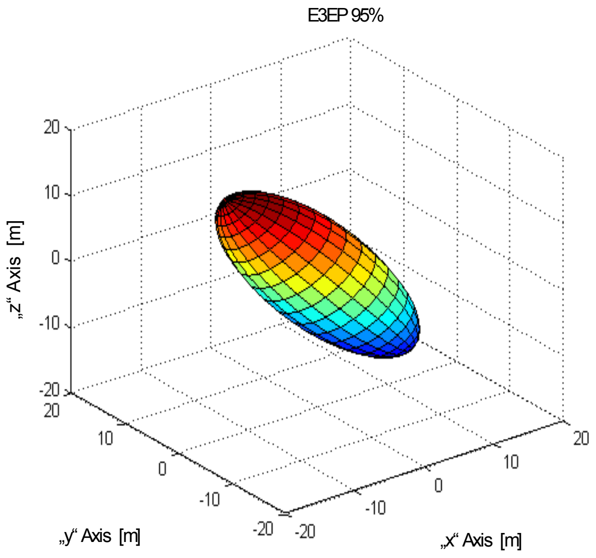

Figure 8: E3EP Error Ellipsoid (95%)

5. CONCLUSION

The paper briefly describes general theoretic attitude to the evaluation of positional errors measurement and an outline of the method of preparations and evaluation of positional data experimental measurement contained in MODE-S onboard responders squitter.
Analysis shows that the methods of error evaluation commonly used by many producers by means of Circular Error Probable (CEP) and Spherical Error Probable (SEP) are admittedly easy, but withhold sufficiently faithful awareness of positional errors

distribution. For comparison of the actual differences, more objective interpretation was chosen in the form of error ellipsoid for 3D measuring.

The real dispersion of positional measuring (GPS data) and the influence of conditions on MODE-S signal reception are still commonly neither known nor published. To investigate the subject, procedure, appropriate device and SW for experimental measuring and evaluation of the positional errors were made ready.

Performed long-time measurements show that under good conditions of signal reception the GPS mean positional stationary error is within the limits of 15 to 30 meters and dynamic error around 6 meters. Such accuracy is comparable to craft size and sufficiently conform the ATC conditions of surveillance. Under these conditions a simpler interpretation of the errors is acceptable by means of CEP and SEP. This statement however doesn't need to be true under worse reception conditions as several times bigger errors had been observed.

Analogous measurement results were also evaluated in dynamic mode - at mobile SQB transmitter position evaluation.

However, the evaluation of the series of MODE-S signal stationary positional measurements indicate, at the same time, enormous dependence on measuring conditions - influence of antenna ambiance, electromagnetic coexistence and the quality of used GPS receiver.

Jamming of GPS signal presents another serious problem of ATC security – investigation of the subject deserves a separate analysis.

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