Basic Mathematical ATM Model for Time Based Navigation In U-Space Environment

Vladimir Milosević

University of Belgrade, Republic of Serbia, vladimir_milosevic@hotmail.rs

Contribution to the State of the Art

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Abstract: Time Based Navigation Mathematical model is a navigational tool which allows instant management of distance, speed and time on more effective way. Time is a kind of specific imaginary dimension which describes real life dynamicity. Most efficient tool for time measuring, which precisely represents nature of time, is a circle with angles inside, well known as "clock". Time Based Navigation Mathematical model is only different way of use of this measuring tool where every aircraft on its route has precise navigational time clock for accurate destination arrival. Implementation of this model can offer higher level of navigational precision in longitudinal and lateral domain, effective speed correction calculations and management in time domain, constant identification and recalculation of total time error and also can be used as safety net tool to define conflicts in UTM Air Space.

Keywords: Digitalization, propulsion, aircraft, U-Space, Electrification, ATM, environmental friendly, zero emissions, arrival management, artificial intelligence.

Introduction

Technical development of the 21st Century has brought vast of different business models and need for more efficient and effective methods for general, private and cargo air transportation. Following recent developments in the air traffic domain some main processes and development areas can be identified as:

- Digitalization of air navigation and air traffic management with the future involvement of artificial intelligence, as augmentation of actual processes and procedures.
- High Altitude Operations ("HAO") with high speed, high power propulsion aircrafts or low speed, low power propulsion aircrafts.
- Further development of vertical take-off and landing capability of aircrafts with quadricopter configuration.
- Introduction of "U-Space" as air space class and need for intensive and effective personal and commuter air-transport for urban areas [1].
- Introduction of ultra-light composite materials for aerodynamically high efficient aircrafts.
- Electrification of aircrafts propulsion systems with the aim to achieve more environmental friendly and zero emissions standards.

All those developments require intelligent Air Traffic Management (ATM) system with more efficient methods for air navigation, aircraft separation and effective real time administration of air operations with intensive data exchange and sharing.

Actual ATM system for general transportation (GAT) has proved its value as very robust and safe but it has many characteristics that have to be changed or adapted in order to introduce solutions from mentioned development areas.

"U-space" is the most ATM demanding domain due to projections of intensive future air traffic in significantly small air space volumes over urban areas [2] what will arise following issues which have to be taken into account:

- Air safety solutions of actual ATM system are based on large buffer volumes which are space demanding.
- Separation methods are based on vertical and lateral separation with complex methods of

longitudinal or time separation models which haven't jet been developed to the level of practical use.
- Navigation precision is calculated according to the sum of errors that are generated due to various reasons without or with weak models for their correction, and basically total navigational error only classify navigation method on different types (e.g. PBN, precision or non-precision approach).
- Procedures for approach and landing consume large areas of space volumes and specialized ATM services need to handle those operations. [3]
- With increase of number of air operations in relatively short period of time actual ATM procedures and methods became more complex and more energy demanding for aircraft propulsion systems with extension of time needed for actual flight of an aircraft (e.g. holding procedures).
- Digitalization of air navigation models require complex and weight demanding IT and communicational ground and aircraft on-board equipment.
- Variety and quantity of data that have to be processed and exchanged are time and capacity demanding what increase latency and bandwidth of real-time data exchange [4].
- Arrival management (AMAN) has significantly short horizon for arriving traffic and air traffic planning and management models are overloaded with rapid increase of traffic.

Following previously mentioned issues intelligent U-Space ATM system has to fulfill different requirements and has to be capable to develop:
- Navigation model with full precision in all four domains (altitude, lateral, longitudinal and time navigation) with automatic navigational error calculation and management.
- Aircraft separation models need horizontal separation as primary method and vertical separation as additional procedure.
- Energy efficient "Direct-to" and "On-Spot landing" ATM procedures with possibility to use charging mode of engines during descend, arrival and landing phases of flight [5].
- Simple and safe methods for high intensity air traffic management in relatively small air volumes.
- Seamless AMAN with extended time horizon for real time air space and ATC capacity planning up to departure and pre-departure phases of air operations.
- Small weight footprint of ground and onboard IT, COM and NAV equipment and small data exchange footprint for U-Space ATM network [6].

Summarizing everything mentioned U-Space environment require robust model of time based navigation which is capable to cover all previously mentioned issues and fully use already introduced achievements in ATM and COM domains.

Basic Mathematical Model for Time based navigation

Idea of Basic Mathematical Model (BMM) comes from theoretical principle of speed correction value which is related to the available time up to "Destination point", which says that:

"Correlating the speed correction value in function with the available time till the destination point (correction time), the resulting speed correction has tendency to infinity as the time for the correction goes toward zero, and vice versa if correction time goes toward infinity."

Practical implementation of this principle says that, in moment when some delay on route is identified, speed correction for that delay has some value and that value grows as correction time toward certain destination leaking out.

Mathematical Model for Time based navigation is a mathematical description of this principle and Time Distance Angle (TDA) is the core of the model which represents the nature of time and speed corrections as an aircraft flies toward destination point. The value of TDA is growing up over the time and it has the value of 180 degrees on the destination point simulating infinite value of speed correction at zero moment of correction time. Calculations of TDA are based on basic geometry of circle and proportion of pages and angles in triangle and basic geometry of TDA is presented on figure 1.

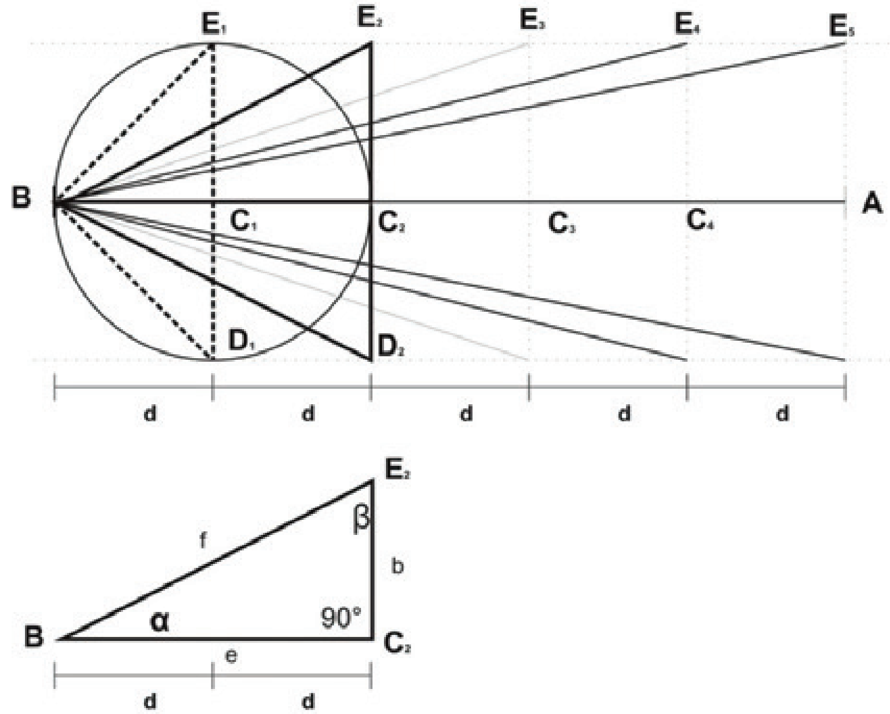

Figure 1.

Mathematical model uses a situation of aircraft trajectory from point A to point B and on that trajectory point C_1 is marked as position of an aircraft. A circle with center in point C_1 with radius d, which refers to the distance of BC_1=d, defining points E_1 and D_1 orthogonally to the aircraft speed vector and the connections of points E_1, B, D_1 will produce the angle of 90^0 ($\sphericalangle E_1BD_1$).

Defining distance d as distance that an aircraft will fly in time period of one minute implies that the angle $\sphericalangle E_1BD_1$ will go from 90^0 till 180^0 in time of one minute. Doing the same thing at point C_2 implies that value of angle $\sphericalangle E_2BD_2$ refers to the time period of two minutes. Extracting $\triangle E_2BD_2$ triangle, the page BC_2 (page e) refers to the page E_2C_2 (page b) in proportion of 2:1. This means that the angles β and α are also in proportion of 2:1 what gives us the value of angle α of 30^0. As the angle α is exact one half of angle ∢E2BD2 than we can conclude that two minutes before the end of aircraft trajectory the angle that connect points orthogonally defined to the aircraft speed vector at the distance that refers to two minute of flight will have value of 60^0. In further text this angle will be called Time Distance Angle (TDA) and distance "d" will be called Time-Distance Value (TDV). Same logic will be applied to all other points from C_2 till C_5 and value of TDA angle will be calculated by formula:

$$TDA = 2 * \frac{90^0}{(n_d + 1)}$$

$$n_d = |\, t_{[min]} \,|$$

Value of n_d refers to the absolute value of number of minutes till the end of trajectory. This formula allows TDA calculations from the beginning of aircraft trajectory.

In real situations during the actual flight, using the same Time-Distance Value (d) at real GNSS position related to position of a Destination Point, the Real TDA will be formed and compared with projected (required) TDA for exact moment of time what defines actual delay or overtime what is expressed as value of Total Time Error (TTE), at figure 2.

TTE Correction - Air and Ground Speed Correction Algorithm

If TTE is identified at early stage of flight the correction by the speed is possible. Any kind of delay at moment C_2 produces aircraft's position C'_2 and lover value of Real

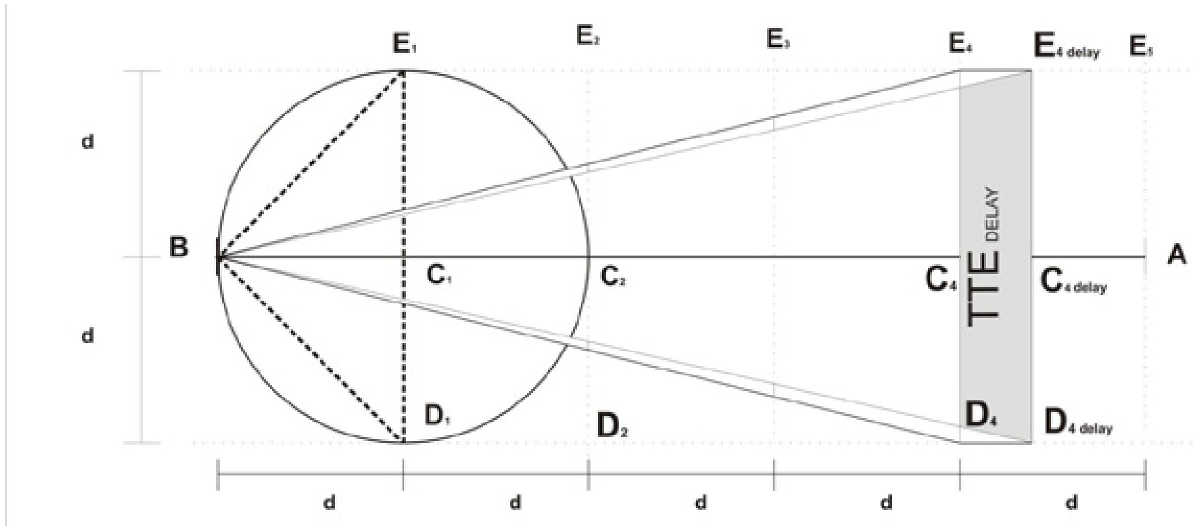

Figure 2.

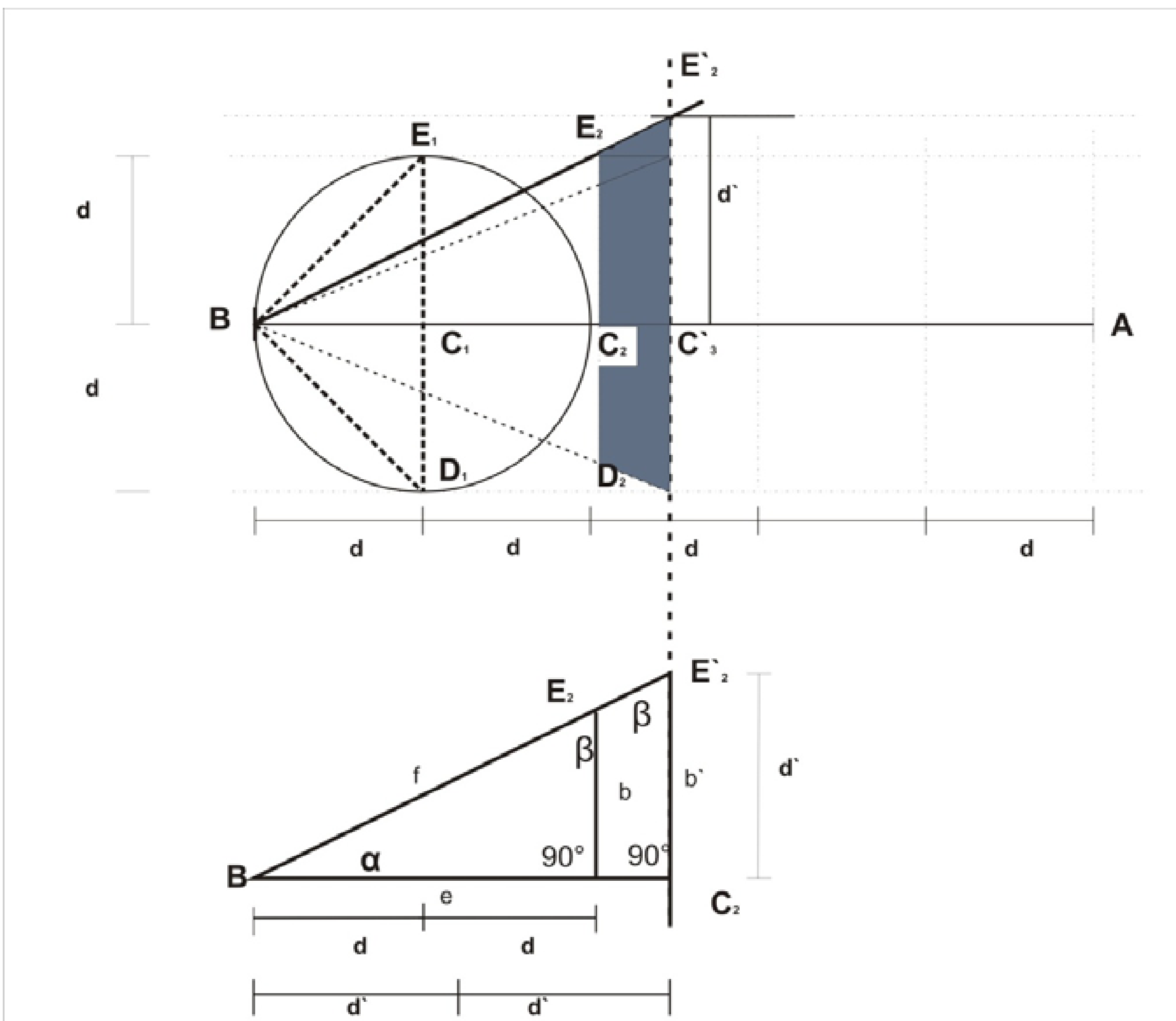

Figure 3.

TDA angle compared to the Projected TDA. Measuring distance C'_2 and E'_2 which will be new Time Distance Value (TDV' or "d'- d prim").

The figure 3 shows that triangles ⊿⊿E_2BC_2 and ⊿⊿ $E'_2BC'_2$ are similar with same angles and proportional triangle pages, what means that,

$BE_2 : E_2C_2 = BE'_2 : E'_2C'_2$

Focusing on TDV' and that it jointly represent time and distance, it can be also used as intensity of speed vector expressed in distance (Nm or km) per minute, and if we multiply it by 60 we will get the required "corrected or calibrated" speed (in knots or km/h) for the accurate time arrival to the Destination Point.

Basic ATM Operational Concept Principles of TDA

In real life TDA construction method can be used for projection of on-screen navigational marker as efficient ground speed manipulation tool followed with real time speed correction calculations. Basically the main task will be to keep required and real TDA marker joined together, using real time speed correction calculations what is described on figure 4.

This model also provides very convenient environment for the use of artificial intelligence and automation of all Time Based Navigation processes, where the position and addresses of marker's pixels on the screen could be compared and used in decision making processes.

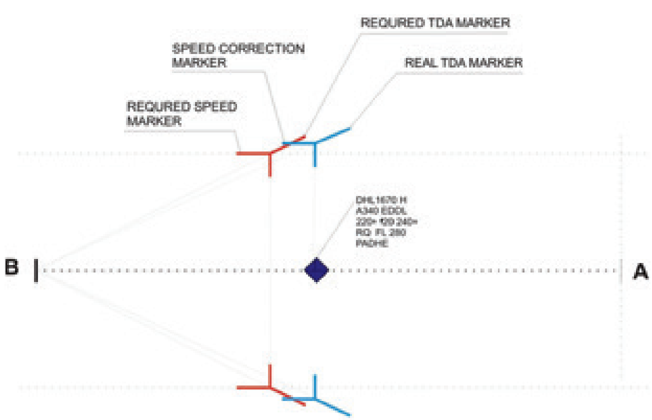

Figure 4.

Different applications of Basic Mathematical Model for Time based navigation

Using the same logic from figure 3. the construction of the algorithm for early UTM conflict identification can be defined for the ATC management. If two different aircrafts at the same moment of time are flying toward the same Destination Point with different distance and different speed but the same Time Distance Angle then this conflict situation has very high probability.

Having in mind that only the value of TDA is used as element of conflict detection it can be applied as a filter and even in a flight planning phase as robust ATM Capacity Flow Management Tool.

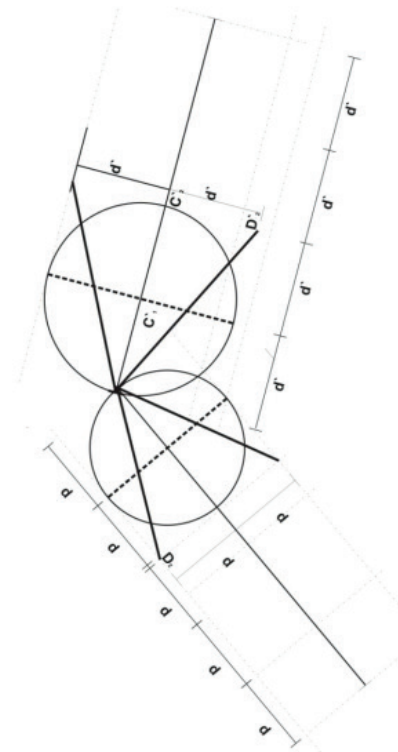

Figure 5.

Advanced characteristics of the Time Based Navigation Mathematical model

Time Based Navigation Mathematical model characteristics can be used to achieve the goals needed for accurate and synchronized ATM for U-Space environment with high level of traffic intensity and dynamicity. The most important of all characteristics could be described as:

- Higher level of navigational precision in longitudinal and lateral domain.
- Effective tool for speed correction calculations and management in time domain.
- Constant identification and recalculation of total time error.
- There is no need for deeper analysis what generates time and navigation errors.

- Can be used as safety net tool to define conflict in air traffic.
- Simplifies arrival and landing procedures.
- Allows construction of "Direct-to" and "On-Spot landing" UTM procedures.
- Harmonize air traffic and provide environment for energy efficient UTM procedures.
- In combination with other aircraft performance management tools can provide environment for Continuous Climb and Descent Operations.

CONCLUSION

Time Based Navigation Mathematical model is a navigational tool which allows instant management of distance, speed and time on different and more effective way, offering possibility that every aircraft on his route has precise navigational time clock for accurate destination arrival.

Implementation of this model can offer higher level of navigational precision in longitudinal and lateral domain, effective speed correction calculations and management in time domain, constant identification and recalculation of total time error and can be used as safety net tool to define conflicts in U-space enviroment.

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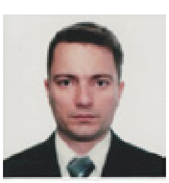
ABOUT THE AUTHORS



Vladimir Milošević has Master of Science degree of Aeronautical Engineering from The Faculty of the Transport and Traffic Engineering of The University of Belgrade. He has 25 years long working experience in aviation as a pilot of The Serbian Air Force. During his career he worked on projects of civil-military cooperation in aviation and regulatory issues in Military Aviation Authority. He also has basic skills of JAVA/SQL Programming and Software Design.

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