Analysis of the Geometric Altimetry to Support Aircraft Optimal Vertical Profiles within Future 4D Trajectory Management

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ABSTRACT
The use of barometric altimetry is to some extent a limiting factor on safety, predictability and efficiency of aircraft operations, and reduces the potential of the trajectory based operations capabilities. However, geometric altimetry could be used to improve all of these aspects. Nowadays aircraft altitude is estimated by applying the International Standard Atmosphere which differs from real altitude. At different temperatures for an assigned barometric altitude, aerodynamic forces are different and this has a direct relationship with time, fuel consumption and range of the flight. The study explores the feasibility of using sensors providing geometric reference altitude, in particular, to supply capabilities for the optimization of vertical profiles and also, their impact on the vertical Air Traffic Management separation assurance processes. One of the aims of the thesis is to assess if geometric altitude fulfils the aeronautical requirements through existing sensors. Also the thesis will elaborate on the advantages of geometric altitude over the barometric altitude in terms of efficiency for vertical navigation. The evidence that geometric altitude is the best choice to improve the efficiency in vertical profile and aircraft capacity by reducing vertical uncertainties will also be shown. In this paper, an atmospheric study is presented, as well as the impact of temperature deviation from International Standard Atmosphere model is analyzed in order to obtain relationship between geometric and barometric altitude. Furthermore, an aircraft model to study aircraft vertical profile is provided to analyse trajectories based on geometric altitudes.

Keywords
Trajectory based operations, Flight profiles, geodetic altimetry, vertical guidance, 4D trajectories.

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INTRODUCTION
Aircraft barometric altimeters have been, basically, the only sensor used to determine aircraft altitude for many years. As a consequence, any intention of using any other sensor which uses a fixed reference geometric vertical altitude has been somehow against the current aeronautical heritage.

Airspace vertical organization is based on isobaric surfaces (Flight Levels). From this structure, aircraft vertical separation is obtained by maintaining 1000ft as nominal separation minima in flight level. This standard has safety issues in relation to it and has been extensively studied in the last decade [1, 2].

However, when aircraft are ascending or descending, close to or below transition altitude/level, near airports, vertical separation minima required is greater, mainly due to uncertainties about the flown vertical profile and the required change of the altimeter reference. Therefore, barometric altimetry requires specific procedure in terms aircraft and Air Traffic Control (ATC) operations which comes with associated pilot and controller workload. The extra workload and operations could lead to inefficient use of the airspace and potential occurrence of human error [3].

Barometric altimetry provides an altitude based on International Standard Atmosphere (ISA) model, which assumes not only a given pressure and temperature at Mean Sea Level (MSL) but is a defined law establishing temperature and pressure evolution with altitude. Nonetheless, this estimated altitude is affected by temperature variation. For example, when temperature given is below that of the standard atmosphere; the altimeter gives an altitude higher than geometric altitude. This fact could be critical in places where the standard temperature profile is different from the real profile. Young and Erik Yee [4] have shown that in Canada differences in altitude can reach up to 340 m.

On the other hand, the use of geometric reference will permit to predefine any vertical (optimal) profile, as done for horizontal routes, in the Flight Management System (FMS), based on best available atmospheric and aircraft data. The planned profile will then be flown under predefined required vertical navigation performance. As an example, today's continuous descent approaches (CDAs) for a complete descent, with close to idle engines regime is not practicable mainly due to the lack of FMS defined geodetic flyable trajectories for vertical profile. In addition, aerodynamic induced forces in steady flight remain constant by isodensity surfaces rather than isobaric surfaces. The maximum lift/drag ratio is density independent, and so the maximum efficiency for steady flight can be easily followed by isodensity surfaces. Moreover, considering that aircraft continuously lose mass, the needed lift for steady flight also decreases, requiring altitude changes for optimal vertical profiles.

At present, positioning sensors and associated avionics on board (Global Positioning System (GPS)/Inertial Navigation System (INS) and Radioaltimeter) are able to estimate 3/4D position in reference to a geodetic reference, local coordinates and time deviations within certain statistical limit. Authors such as Robert A. Gray and Peter S. Maybeck [5] researched on the possible use of GPS/INS/BARO and Radar Altimeter System in Category I/II precision approach and based on this, ILS look alike approaches are being implemented today.

OBJECTIVE

The aim of the present study is to analyse the possibility of using geometric altimetry to support aircraft optimal vertical profiles for the future 4D trajectory management.

The objectives of the study are presented below:

1. To assess if geometric altitude fulfils the aeronautical requirements through the existing sensors (INS, GNSS/GPS, Radar Altimeter, Air Data Computer).
2. To show its advantages over the barometric altitude in terms of efficiency for vertical navigation.
3. To show evidences that geometric altitude could be the best choice for 4D trajectories management.

CURRENT SITUATION

Atmosphere Study

Atmosphere is essential in air navigation because it is the domain where the aircraft fly. To develop a safe and correct flight, it is necessary to know its characteristics, such as: temperature, pressure, wind vector, etc. At present, aircraft safety separation of 1000ft is established by using radio altimeter system. The system uses static and dynamic pressure measurements to acquire pressure information, which is converted into altitude using the International Standard Atmosphere.

ICAO Standard Atmosphere [6], which was established in 1952, is based on ideal gas, without dust, humidity and water vapor and stable relative to the Earth. With these hypotheses, it is possible to apply the hydrostatic equation (Eq. 1) for an air column.

$$\frac{dp}{p} = -\frac{g_0}{R_a T} dh \qquad \text{(Eq. 1)}$$

where:

- p_s is the pressure,
- g_0 is the acceleration of gravity at MSL which is equal to 9.80665m/s^2,
- R_a is the gas constant which is equal to 287.0531 J/kg·K,
- T is the temperature,
- h is the altitude.

When aircraft are in the approach phase at the altitude of transition, Air Traffic Control sends them the QNH information so that all aircraft have the same reference in order to maintain a secure vertical separation.

To separate aircraft using altimeter information, it is important that the altimeters have a great accuracy in their static pressure measurements. The pressure error or the position errors, as it is sometimes called, is determined experimentally. It is a function of the Mach [7] and in the worst case produces an error value of 180Pa (150Pa due to uncertainty error and 30Pa due to sensor). Aircraft travelling at the tropopause give equivalent error in altitude of 69m (227ft). At lower altitudes this error is around 30Pa, which gives an altitude error of less than 3.3m (11ft) [7].

ISA consider a linear dependency (-6.5 degree per 1000m) of temperature with altitude in the troposphere (MSL-11.000m) and constant values in the tropopause (11.000m-20.000m) [6]. Having this temperature model, the hydrostatic equation (Eq. 1) can be solved. To evaluate the difference between barometric altitude and geometric altitude, the next step will be to determine the temperature deviation from the ISA temperature model.

Many researches have measured atmospheric characteristics in terms of the vertical profile with different instruments, such as: balloons, LIDAR, radar, sounding rocket, TIMED spacecraft.

In Hainán (China) on June 3, 2011, the vertical temperature profile was measured [8] using some the above mentioned instruments. From this research a maximum temperature deviation of 25K at 17.000m was observed.

In an urban area of Beijing (China) on November 2, 2009 a similar experiment was performed and the maximum temperature deviation was 15 degree at 16.000m [9]. Again, in Kyotanable (Japan) on May 13, 2000, the temperature difference was about 10 degrees [10].

Research performed by NASA on the US Standard Atmosphere [11] shows a global maximum temperature deviation from the ISA model of 65K at MSL.

Another study undertaken by Garrido-López and Gómez [12], showed the relationship between barometric and geometric altitude using the hydrostatic and ideal gas equation as shown in (Eq. 2):

$$\frac{dH_b}{dh} = \frac{T_{ISA}}{T_{ISA} + T_{Dev}} \square \frac{T}{T_{ISA}} \qquad \text{(Eq. 2)}$$

where,

- H_b is the pressure altitude,
- h is the geometric altitude,
- T_{ISA} is the temperature from ISA model,
- T_{Dev} is the difference from the ISA temperature model to the actual temperature.

To evaluate the T_{Dev} from the (Eq. 2), a statistical study using information from about 95 radiosondes stations of World Meteorological Organization (WMO) [13] collected between July to September, 1996 was performed. The study was based on the calculation of the standard deviation of the collected temperature data for each flight level, as shown by the dots in figure 1.

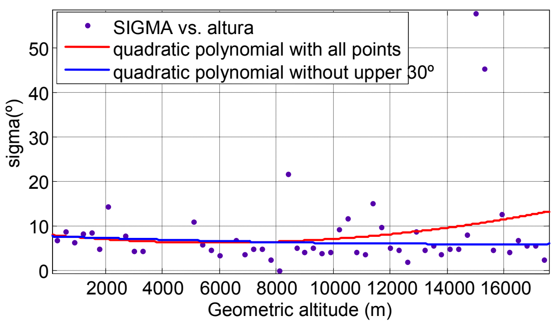

Figure 1: Temperature standard deviation vs. Geometric altitude

A continuous relationship between flight levels and temperature deviation from the ISA temperature was achieved using quadratic polynomial approximation by applying Least Mean Square (LMS) calculation. The result from the calculation can be seen in figure 1.

$$\frac{T_{Dev}}{T_{ISA}} = \frac{5.184 \cdot 10^{-8} h^2(m) - 6.141 \cdot 10^{-4} h(m) + 8.069}{288.15 - \frac{6.5}{1000} H_b(m)} \qquad \text{(Eq. 3)}$$

(Eq. 3) shows the mathematical expression for the ratio of temperature deviation with respect to ISA temperature as a function of geometric altitudes below 11.000m.

$$\frac{dH_b}{dh} \square \frac{5.184 \cdot 10^{-8} h^2 - 6.141 \cdot 10^{-4} h + 8.069}{288.15 - \frac{6.5}{1000} h} \qquad \text{(Eq. 4)}$$

Substituting (Eq. 3) into (Eq. 2), a differential equation (Eq. 4), which relates the geometric and the barometric altitude, is obtained. This differential equation is solved by assuming that MSL pressure is equal to ISA pressure at MSL.

Figure 2 shows a nearly linear relationship between the relative barometric altitude to the geometric altitude from 0 to 300m. This relationship is relevant for the development of the thesis, because most of the information from aircraft is given based on barometric altitude but the research seeks to analyse trajectories based on geometric altitude.

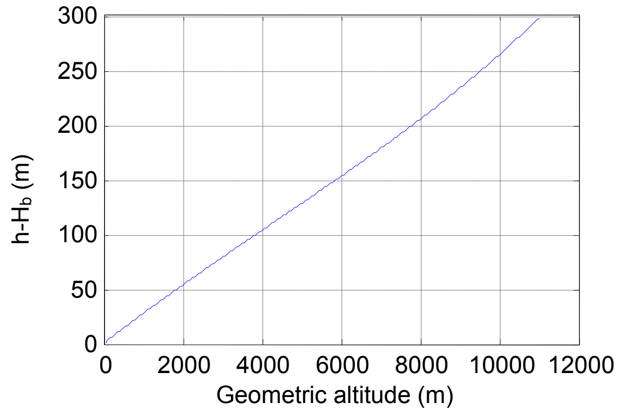

Figure 2: Relative barometric altitude vs. geometric altitude

Aircraft Trajectory Simulator

A three degrees of freedom (3DOF) [14] aircraft model was developed to study the geometric vertical routes in terms of flight feasibility and flight efficiency. For the design and implementation of the simulation, MATLAB SIMULINK software environment was used [15].

The simulator has three main sections: inputs, aircraft model and scenario definition and the longitudinal flight mechanic, as shown in figure 3.

Throttle lever position (P) and flight path angle (γ) are the inputs of the system.

The second section is divided into 2 main groups: physical environment and aircraft characteristics.

The physical environment subsection constitute the dynamic pressure and the wind vertical profile (ω(h)). The dynamic pressure is calculated by making use of the ISA (pressure (p), Temperature (T), Lapse rate temperature (α)) and the gravity acceleration (g). The vertical wind profile is estimated from measured data.

In the aircraft characteristics subsection, the following forces are evaluated: drag (D), thrust (T) and weight (W). The drag is calculated from the dynamic pressure and the aircraft data; (Wing surface (S_W), Drag polar values (C_{d0}, k), and Weight (W)). The thrust is estimated using the throttle lever position and the vertical power profile. The weight (W) is derived from the vertical power profile and the thrust specific fuel consumption (C_p).

The last section encloses the 3DOF equations.

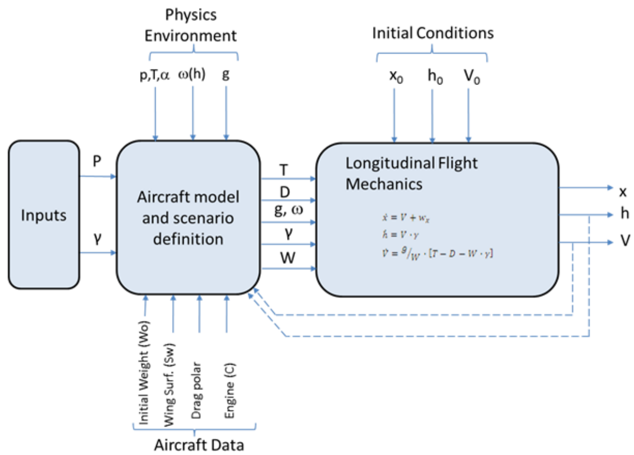

Figure 3: Aircraft trajectory simulator

FUTURE WORK

As of now, analysis of the differences between geometric and barometric has been established. This paves the way for the next stage of the research work based on geometric altimetry which includes:

1. Assessment of the impact on aircraft when they follow geometric predefined vertical routes in terms of flight feasibility and efficiency.
2. Assessment of its impact on the vertical airspace organization to provide separation assurance within the ATM/ATC.
3. Assessment of the robustness of the candidate sensors (safety issues, accuracy, integrity and availability).
4. Evaluation of enhancement in terms of 4D trajectory management applied to the predictability and efficiency of flights.

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