En-Route Trajectory calculation using Flight Plan Information for Effective Air Traffic Management

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Abstract—Trajectory modeling is foundational for 4D-Route modeling, conflict detection and air traffic flow management. This paper proposes a novel algorithm based Vincenty's fomulas for trajectory calculation, combined with the Dijkstra algorithm and Vincenty's formulas. Using flight plan simulations our experimental results show that our method of En-route trajectory calculation exhibits much improved performance in accuracy.

Keywords—ATC, ATM, Trajectory Prediction, ATFM

1. INTRODUCTION

Air Traffic Control (ATC) systems improve the safety and efficiency of air traffic by preventing collisions with other aircraft and obstacles and by managing aircraft navigation status [1].

To achieve these purposes, air traffic control systems identify aircraft and display their location, display and distribute flight plan data, provide flight safety alerts, and process controllers' requests [2].

Despite technological advances in navigation, communication, computation and control, the Air Traffic Management (ATM) system is still, to a large extent, built around a rigidly structured airspace and centralized around mostly human-operated system architecture. The increasing demands of air traffic are stressing current ATM practices to their limits and the need for alternatives of higher capacity arises [3].

In keeping with the recent increase in air traffic a more efficient air traffic control method is required. The accuracy of trajectory predictions in En-route airspace impacts ATM conflict predictions and Estimated Times of Arrival (ETA) to control fixes. For the airspace user, inaccurate trajectory predictions may result in less-than-optimal maneuver advisories in response to a given traffic management problem [3, 4].

These include missed advisories and false advisories. Missed advisories refer to the lost opportunity of resolving a traffic management problem in a manner most efficient to the airspace user. False advisories refer to the suggestion of an unnecessary maneuver that may cause an aircraft to depart from its most efficient or user-preferred, trajectory.

A limiting factor in the accurate prediction of aircraft trajectories is the difficulty in obtaining

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precise trajectory calibration and intent data for individual flights. Trajectory calibration data refers to aircraft state, aircraft performance, and atmospheric characteristics that influence the external forces acting on the aircraft.

Trajectory intent information includes the anticipated route, speed profile, and maneuvering procedure of the aircraft over the trajectory prediction time horizon.

In this paper we propose an efficient method of En-route trajectory calculation using flight plan information.

The remainder of this paper is organized as follows: In the next section, trajectory calculation techniques and theoretical background about trajectory calculation are presented. We describe our En-route trajectory calculation algorithm in Section 3. In Section 4 we present some experimental results of our proposed scheme, and then we end with our conclusions in Section 5.

2. TRAJECTORY CALCULATION TECHNIQUES

2.1 Trajectory calculation theory

Let us first consider a fairly simplified model for our trajectory design problem. The set of flows shall be arbitrarily chosen. A flow is defined as a set of flights between a departure airport and an arrival airport. The following simplifications are made: The airspace is considered as an Euclidean space, where all airports are at altitude 0. Latitudes and longitudes on the ellipsoid earth surface are converted into (x, y) coordinates by a stereographic projection, and the altitude in feet shall be our z coordinate [5].

All aircraft fly with identical performances and follow linear slopes of climb and descent.
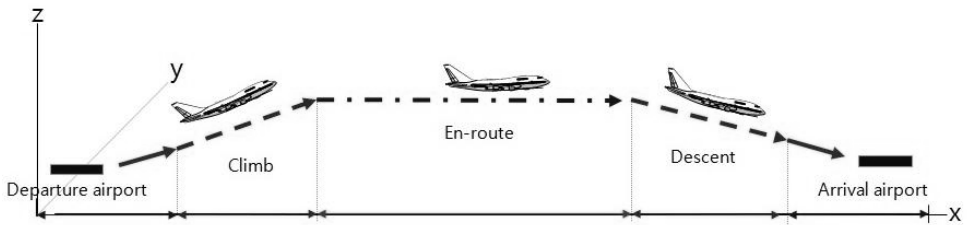

Fig. 1. Basic model of a default trajectory

2.2 Parameters for trajectory calculation

For trajectory calculation, we must consider the concept of speed, speed variation by altitude adjustment and wind parameters.

First, airspeed is the speed of a trajectory calculation relative to the air. The common conventions for qualifying airspeed are: indicated airspeed (IAS), calibrated airspeed (CAS), true airspeed (TAS), and ground speed (GS).

Indicated airspeed (IAS) is the Airspeed Indicator Reading (ASIR) uncorrected for instrument, position, and other errors. From current EASA definitions: Indicated airspeed means the speed of an aircraft as shown on its pitot-static airspeed indicator calibrated to reflect standard atmosphere adiabatic compressible flow at sea level uncorrected for airspeed system errors.

Most airspeed indicators show the speed in knots (i.e. nautical miles per hour). Some light aircraft have airspeed indicators showing speed in miles per hour.

Calibrated airspeed (CAS) is indicated airspeed corrected for instrument errors, position error and installation errors.

Calibrated airspeed values less than the speed of sound at standard sea level (661.4788 knots) are calculated as follows:

$$V_C = A_0 \sqrt{5\left[\left(\frac{Q_C}{P_0} + 1\right)^{\frac{2}{7}} - 1\right]}$$
(1)

Where

V_C is the calibrated speed.

Q_C is the impact pressure sensed by the pitot tube.

P_0 is 29.92126 inches Hg; static air pressure at standard sea level

A_0 is 661.4788 knots; speed of sound at standard sea level

This expression is based on the form of Bernoulli's equation applicable to a perfect, compressible gas. The values P_0 and A_0 are consistent with the International Standard Atmosphere (ISA).

True airspeed (TAS) is the physical speed of the aircraft relative to the air surrounding the aircraft. The true airspeed is a vector quantity. The relationship between the true airspeed (V_t) and the speed with respect to the ground (V_g) is represented thusly:

$$V_t = V_g - V_w$$
(2)

Where

V_w is Wind speed vector.

Aircraft flight instruments, however, don't compute true airspeed as a function of groundspeed and wind speed. They use impact and static pressures as well as a temperature input. Basically, true airspeed is calibrated airspeed that is corrected for pressure altitude and temperature. The result is the true physical speed of the aircraft plus or minus the wind component. True Airspeed is equal to calibrated airspeed at standard sea level conditions.

The simplest way to compute true airspeed is using a function of Mach number

$$V_t = A_0 \cdot M \sqrt{\frac{T}{T_0}}$$
(3)

Where M is Mach number, T is Temperature (Kelvins) and T_0 is Standard sea level temperature (288.15 Kelvins)

Second, speed variation by altitude adjustment refers to when aircraft are climbing or descending.

The Rate of Climb (RoC) is the speed at which an aircraft increases its altitude. This is most often expressed in feet per minute and can be abbreviated as ft/min.; elsewhere, it is commonly expressed in meters per second, abbreviated as m/s. The rate of climb in an aircraft is measured with a Vertical Speed Indicator (VSI) or Instantaneous Vertical Speed Indicator (IVSI). The rate of decrease in altitude is referred to as the rate of descent or sink rate. A decrease in altitude

corresponds with a negative rate of climb.

There are two airspeeds relating to optimum rates of ascent, referred to as Vx and Vy.

Vx is the indicated airspeed for best angle of climb. Vy is the indicated airspeed for best rate of climb. Vx is slower than Vy.

Climbing at Vx allows pilots to maximize the altitude gain per unit ground distance. That is, Vx allows pilots to maximize their climb while sacrificing the least amount of ground distance. This occurs at the speed for which the difference between thrust and drag is the greatest (maximum excess thrust). In a jet airplane, this is approximately minimum drag speed, or the bottom of the drag vs. speed curve. Climb angle is proportional to excess thrust.

Climbing at Vy allows pilots to maximize the altitude gain per unit time. That is, Vy, allows pilots to maximize their climb while sacrificing the least amount of time. This occurs at the speed for which the difference between engine power and the power required to overcome the aircraft's drag is the greatest (maximum excess power). Climb rate is proportional to excess power.

Vx increases with altitude and Vy decreases with altitude. Vx = Vy at the airplane's absolute ceiling, the altitude above which it cannot climb using just its own lift.

Last, we consider wind parameters. Wind parameters can be divided into two components (weather fronts and thermal winds) on a large scale.

Weather fronts are boundaries between two masses of air of different densities, or different temperature and moisture properties, which normally are convergence zones in the wind field and are the principal cause of significant weather. Within surface weather analyses, they are depicted using various colored lines and symbols.

The air masses usually differ in temperature and may also differ in humidity. Wind shear in the horizontal occurs near these boundaries. Cold fronts feature narrow bands of thunderstorms and severe weather, and may be preceded by squall lines and dry lines.

Cold fronts are sharper surface boundaries with more significant horizontal wind shear than warm fronts. When a front becomes stationary, it can degenerate into a line which separates regions of differing wind speed, known as a shear line, though the wind direction across the feature normally remains constant. Directional and speed shear can occur across the axis of stronger tropical waves, as northerly winds precede the wave axis and southeast winds are seen behind the wave axis.

Horizontal wind shear can also occur along local land breeze and sea breeze boundaries.[

Thermal wind is a meteorological term not referring to an actual wind, but a difference in the geostrophic wind between two pressure levels p_1 and p_0, with $p_1 < p_0$; in essence, wind shear. It is only present in an atmosphere with horizontal changes in temperature.

In a barotropic atmosphere, where temperature is uniform, the geostrophic wind is independent of height. The name stems from the fact that this wind flows around areas of low (and high) temperature in the same manner as the geostrophic wind flows around areas of low (and high) pressure.

$$f_{VT} = K \times \nabla(\varphi_1 - \varphi_0) \tag{4}$$

where the ϕ_x are geopotential height fields with $\varphi_1 > \varphi_0$, f is the Coriolis parameter, and $\boldsymbol{k}$ is the upward-pointing unit vector in the vertical direction. The thermal wind equation does not determine the wind in the tropics. Since f is small or zero, such as near the equator, the equation

reduces to stating that $\nabla(\theta_1 - \theta_o)$ is small. This equation basically describes the existence of the jet stream, a westerly current of air with maximum wind speeds close to the tropopause which is (even though other factors are also important) the result of the temperature contrast between equator and pole.

3. PROPOSED EN-ROUTE TRAJECTORY CALCULATION ALGORITHM

This section describes the method for computing the various parameters used to compute a flight plan and our En-route calculation algorithm.

First of all, we need to extract route information from the flight plan. The flight plan message format is shown in the table below.

By enumerating type 15 route information among Parsed flight plans, we can find a particular confirmed aircraft's waypoints and altitude (or speed) variations.

Waypoints consist of latitude and longitude. In accordance, for measuring the distance between waypoints over a flight information region, the curvature of the Earth must be taken into consideration.

As a rough estimate, we could assume the Earth is a sphere.

$$dN = R\vartheta\varnothing \tag{5}$$

$$dE = Rcos\vartheta\varnothing\lambda \tag{6}$$

Where R is the radius of the Earth (average of 6378.1 km) and the differences in latitude and longitude are in radians, the distance is 447.47 km. This method is a valid assumption over very small distances, however, over large distances we need to account for the non-uniformity of the Earth. The Earth is not actually a sphere; it is an ellipsoid of revolution, 21 km shorter on the North - South direction than the East - West direction.

The flattening at the poles is caused by the centrifugal force of the spinning Earth. Because of this flattening, the radius of the Earth is not a constant value as we assume for Spherical Earth coordinates.

Table 1. Flight plan message format

	Not currently used	Not currently used	Message type¹ number and reference data	Not currently used	Description of emergency	Not currently used	Aircraft identification and SSR Mode and Code	Flight Rules and type of flight	Number and type of aircraft and wake turbulence category	Equipment	Not currently used	Not currently used	Departure aerodrome and time	Estimate data	Route	Destination aerodrome and total estimated elapsed time alternate aerodrome(s)	Arrival aerodrome and time	Other information	Supplementary information	Alerting search and rescue information	Radio failure information	Amendment	
DESIGNATOR																							
MESSAGE TYPE		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	FIELD TYPE NUMBER
Filed flight plan	FPL			■				■		●				●		●	●		●					Filed flight plan messages and associated update messages

● This field begins a new line when the message is printed in page teletypewriter form.

A more accurate method of measuring the distance between two points on the surface of the Earth is Vincenty's Formula. It is accurate to 0.5 mm over a distance of a few centimeters to nearly 20,000 km.

Given the coordinates of the two points (φ_1, λ_1) and (φ_2, λ_2) the Vincenty's inverse method finds the azimuths α_1, α_2 and ellipsoidal distance s.

Calculate reduced latitude U_1 ($\arctan[(1-f)\tan\varphi_1]$, U_2($\arctan[(1-f)\tan\varphi_2]$, and L, and set initial value of $\lambda = L$. Then iteratively evaluate the following equations until λ converges.

$$sin\sigma = \sqrt{(cosU_2 sin\lambda)^2 + (cosU_1 sinU_2 - sinU_1 cosU_2 cos\lambda)^2} \tag{7}$$

$$cos\sigma = sinU_1 sinU_2 + cosU_1 cosU_2 cos\lambda \tag{8}$$

$$\sigma = arctan\frac{sin\sigma}{cos\sigma} \tag{9}$$

$$cos(2\sigma_m) = cos\sigma - \frac{2sinU_1 sinU_2}{cos^2\alpha} \tag{10}$$

$$sin\alpha = \frac{cosU_1 cosU_2 sin\lambda}{sin\sigma} \tag{11}$$

$$cos^2\alpha = 1 - sin^2\alpha \tag{12}$$

$$C = \frac{f}{16}cos^2\alpha[4 + f(4 - 3cos^2\alpha)] \tag{13}$$

$$\lambda = L + (1 - C)fsin\alpha\{\sigma + Csin\sigma[cos(2\sigma_m) + Ccos\sigma(-1 + 2cos^2(2\sigma_m)]\} \tag{14}$$

When λ has converged to the desired accuracy, evaluate the following:

$$u^2 = cos^2\alpha\frac{a^2-b^2}{b^2} \tag{15}$$

$$A = 1 + \frac{u^2}{16384}\{4096 + u^2[-768 + u^2(320 - 175u^2)]\} \tag{16}$$

$$B = \frac{u^2}{1024}\{256 + u^2[-128 + u^2(74 - 47u^2)]\} \tag{17}$$

$$\Delta\sigma = Bsin\sigma\{cos(2\sigma_m) + \frac{1}{4}B[cos\sigma(-1 + 2cos^2(2\sigma_m)$$
$$(-3 + 4sin^2\sigma)(-3 + 4cos^2(2\sigma_m))]\} \tag{18}$$

$$s = bA(\sigma - \Delta\sigma) \tag{19}$$

$$\alpha_1 = arctan(\frac{cosU_2 sin\lambda}{cosU_1 sinU_2 - sinU_1 cosU_2 cos\lambda}) \tag{20}$$

$$\alpha_2 = arctan(\frac{cosU_1 sin\lambda}{-sinU_1 cosU_2 + cosU_1 sinU_2 cos\lambda}) \tag{21}$$

We can compute azimuths (α_1, α_2) and distance s.

4. EXPERIMENTAL RESULTS OF PROPOSED SCHEME

Performance of the trajectory calculation algorithm was measured using a real flight plan. The original message and Parsed results are shown in the table below.

Table 2. Original message and Parsed results

Original message	Parsed results
(FPL-KAL722-IS-A333/H-SXDHIJPRWYZ/SD-RJBB0030-N0448F340 DCT MAIKO DCT WENDY DCT SHION DCT SOUJA Y324 STAGE Y38 SAPRA G585 GOTLO/N0472F380 BULLS DCT-RKSI0133 RKSS-EET/RKRR0044 REG/HL7720 SEL/MPFG DAT/SV NAV/RNAV1 RNAV5 RNVD1E2A1 RMK/TCAS EQUIPPED)	Aircraft ID : KAL722 Flight rules : I Flight type : S Aircraft Type : A333 Wake Turbulence Category : H Radio/Comm/Nav Equipment : SXDHIJPRWYZ Surveillance Equip : SD Departure Aerodrome : RJBB Departure Time : 0030 Cruising speed or Mach number : N0448 Cruising Level : F340 Route : DCT MAIKO DCT WENDY DCT SHION DCT SOUJA Y324 STAGE Y38 SAPRA G585 GOTLO/N0472F380 BULLS DCT Destination Aerodrome : RKSI Total Estimated Elapsed Time : 0133 Alternative Aerodrome : RKSS Other Information : EET/RKRR0044 REG/HL7720 SEL/MPFG DAT/SV NAV/RNAV1 RNAV5 RNVD1E2A1 RMK/TCAS EQUIPPED

Using Departure aerodrome, cruising speed (or Mach number), route and arrival aerodrome, trajectory calculation results are shown in the table below.

Table 3. Original message and Parsed results

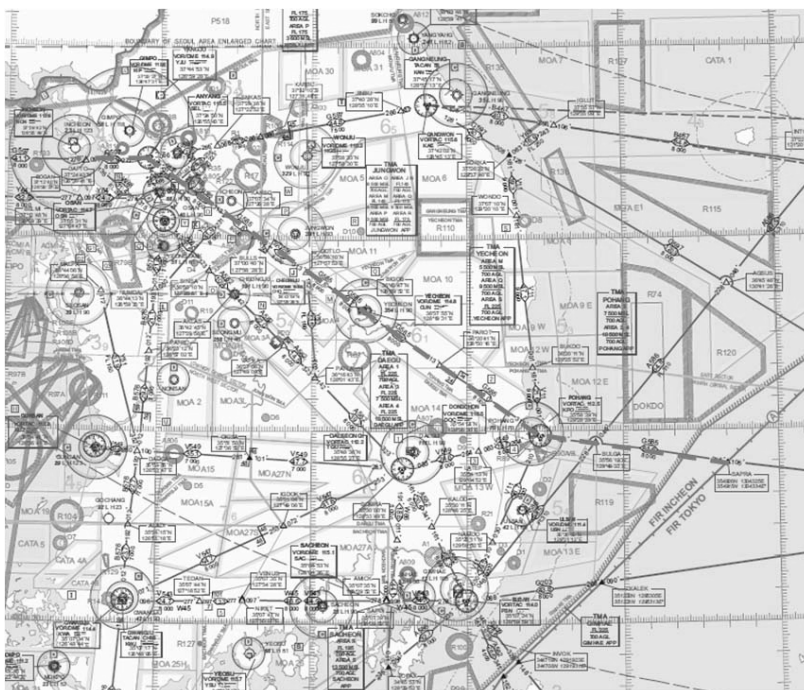|	Waypoint1	Waypoint2	Distance [Km]	Speed (knot/km/h)	Flight Level	Elapsed time[min]
1	SARPA	BULGA	82.061	N0448(628.34)	F340	7.83
2	BULGA	KPO	31.739	N0448(628.34)	F340	3.03
3	KPO	PAROT	69.024	N0448(628.34)	F340	6.59
4	PAROT	CUN	57.008	N0448(628.34)	F340	5.44
5	CUN	BIGOB	17.585	N0448(628.34)	F340	1.67
6	BIGOB	GOTLO	23.082	N0472(873.75)	F380	1.58
7	GOTLO	BULLS	34.007	N0472(873.75)	F380	2.33
8	BULLS	KAKSO	21.221	N0472(873.75)	F380	1.45
9	KAKSO	KALMA	35.692	N0472(873.75)	F380	2.45
10	KALMA	SEL	19.772	N0472(873.75)	F380	1.35
11	SEL	DAPTO	36.956	N0472(873.75)	F380	2.53
12	Total		428.147			36.25

Fig. 2. Simulation results

Fig. 3. Aircraft trajectory presentation on map

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5. CONCLUSION

In this paper we propose efficient En-route trajectory calculation using flight plan information. Experimental results show that our En-route trajectory calculation exhibits much improved performance in accuracy. The applicability of the proposed algorithm is manifold in the trajectory prediction and modeling of such things as Rocket positioning control and Aeronautical Traffic Flow Management systems (ATFM).

It is further suggested that henceforth the proposed algorithm be extended to trajectory modeling, as it may further enhance 4D trajectory predictions.

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