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OPTIMAL THREE-DIMENSIONAL RANGE CRUISE OF A DUAL-FUEL HYPERSONIC VEHICLE

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Abstract

The optimization of the overall cruise trajectory of a two-staged dual-fuel hypersonic flight system with in-flight refueling of the carrier stage is subject of this paper. The flight system performs a range cruise until separation after which the carrier stage equipped with an air breathing powerplant (turbo and ram jet engines combination) returns to its launch site. The rocket propelled orbital stage conducts an ascent to nominal orbit.
The performance requirement for the carrier stage is to reach any latitude on the northern hemisphere from a launch site in Southern Europe. A promising approach for attaining such an extreme performance goal is the dual-fuel concept. This concept basically employs kerosene and liquid hydrogen of which kerosene is used for the turbo jet engines in subsonic and supersonic flight while hydrogen is applied for the ram jet engines in the hypersonic region. The use of kerosene provides an in-flight refueling capability which is not possible with an all-hydrogen-propelled vehicle because of safety reasons. Investigations were made for one, two and three in-flight refuelings. In the case of three in-flight refuelings it is possible to reach the equator from a start point at 43.5° latitude. Thus, it is possible to attain every latitude on the northern hemisphere.

Nomenclature

b^*	fuel consumption factor
f	function
f_α	thrust factor for angle of attack dependency
g	acceleration due to gravity
g_0	acceleration due to gravity for $h = 0$
h	altitude
m	mass of the flight system
m_{Ker}	mass of kerosene in tanks
m_{LH2}	mass of liquid hydrogen in tanks
$\dot{m}_F$	fuel mass flow
$m_{F,tot}$	total fuel mass
n_z	load factor
$\bar{q}$	dynamic pressure, $\bar{q} = (\rho/2)V^2$
r_E	radius of the Earth
C_D	drag coefficient
C_{D0}	zero lift drag coefficient
C_{DF}	friction drag coefficient
C_{DP}	profile drag coefficient
C_{DW}	wave drag coefficient
C_L	lift coefficient
D	drag
L	lift
M	Mach number
S	reference wing area
T	thrust
T^*	thrust with equivalence ratio of 1

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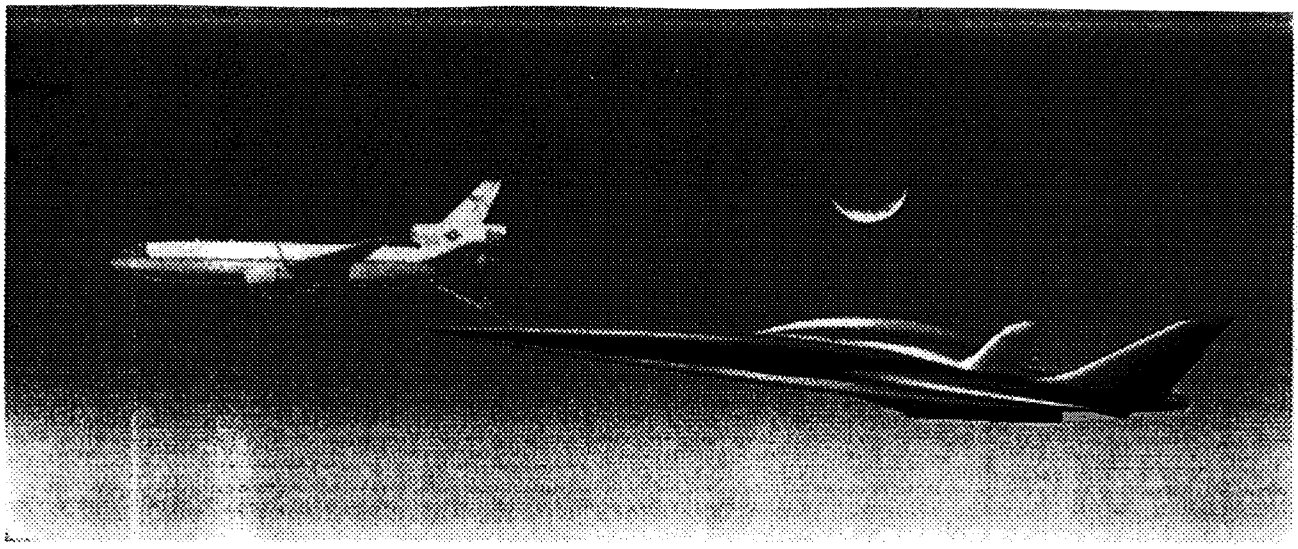

Figure 1: In-Flight Refueling

$T^*_{6^o}$	T^* for $\alpha = 6^o$
V	velocity
V	volume of fuselage
α	angle of attack
δ_e	elevator deflection
δ_T	throttle setting
ϵ_T	thrust vector angle
γ	flight path angle
μ_a	bank angle
ϕ_L	equivalence ratio
χ	azimuth angle
ω_E	angular velocity of the Earth
Δ	geocentric latitude
Λ	geographic longitude

Introduction

New concepts for space transportation are proposed and investigated in various countries as a means for improving the space transportation capability and for reducing costs. A promising concept which is considered in this paper is a two-staged flight system consisting of a winged carrier stage with an airbreathing engine (turbo-ram-jet) and a winged orbital stage propelled by rockets.
The goal is a flexibilisation of the reachable orbit from a fixed starting point. For the investigations the starting point is assumed to be at 43.5 deg northern latitude. A maximum flexibility is considered to be obtained when the flight system can perform the separation at the equator. To achieve this goal it is necessary that the carrier stage has a corresponding range capability.
For the investigated flight system the range of the carrier stage is basically not sufficient. In order to enlarge the range, in-flight refueling is considered. The nominally used liquid hydrogen is not qualified for in-flight refueling, due to the low boiling point (about 20 K at 1 bar) and the highly flammability. As an alternative, the turbo-jet engine may be operated with kerosene till Mach 3.5, and then the ram-jet engines with liquid hydrogen are used. This application of different fuels is known as dual-fuel concept [1, 2, 4, 5]. Thus, a range flight at Mach numbers below 3.5 with in-flight refueling of kerosene can be performed.

Dual-Fuel Concept

Two aspect are of concern with regard to the range improvement offered by the dual-fuel concept.
The first aspect relates to a drag reduction which is basically due to a fuselage decrease. Considering the overall flight system mass as constant, the volume of the tanks can be reduced because of the higher density of kerosene when compared with liquid hydrogen. As a consequence, the fuselage volume can be decreased so that a reduction of the zero lift drag results.

	density [kg/m^3]	calorific value [MJ/kg]
kerosene	793.0	42.0
liquid hydrogene	70.8	120.0

Table 1: density and calorific value of fuels

The second aspect with regard to a range improvement concerns the possibility of in-flight refueling (Fig. 1). In-flight refueling is basically a means for range improvement. Further, it can be used to compensate for the effect of the lower mass specific calorific value of kerosene (Table 1).
An illustration showing schematically the flight profile considered in this paper is presented in Fig. 2.

Figure 2: Flight Plan

Modelling of the Nominal Flight System

For the trajectory optimization problem, the usual mass point modelling is applied for describing the flight system dynamics. With reference to a rotating spherical Earth, the equations of motion can be expressed as (Fig. 3):

$$\dot{V} = \frac{T\cos(\alpha+\epsilon_T) - D}{m} - g\sin\gamma + \omega_E^2 (r_E + h) \cdot \cos\Delta\,(\sin\gamma\cos\Delta - \cos\gamma\sin\Delta\cos\chi)\,,$$

$$\dot{\gamma} = \frac{T\sin(\alpha+\epsilon_T) + L}{mV}\cos\mu_a + \cos\gamma\left(\frac{V}{r_E + h} - \frac{g}{V}\right) + 2\omega_E\cos\Delta\sin\chi + \frac{\omega_E^2(r_E+h)}{V}\cos\Delta\,(\cos\gamma\cos\Delta + \sin\gamma\sin\Delta\cos\chi)\,,$$

$$\dot{\chi} = \frac{T\sin(\alpha+\epsilon_T) + L}{mV\cos\gamma}\sin\mu_a - \frac{V}{r_E + h}\cos\gamma\sin\chi\tan\Delta - 2\omega_E(\tan\gamma\cos\Delta\cos\chi - \sin\Delta) + \frac{\omega_E^2(r_E+h)}{V\cos\gamma}\sin\Delta\cos\Delta\sin\chi, \quad (1)$$

$$\dot{\Delta} = \frac{V\cos\gamma\cos\chi}{r_E + h},$$

$$\dot{\Lambda} = \frac{V\cos\gamma\sin\chi}{(r_E + h)\cos\Delta},$$

$$\dot{h} = V\sin\gamma,$$

$$\dot{m} = -\dot{m}_F$$

with

$$g = g_0\left(\frac{r_E}{r_E + h}\right)^2 . \quad (2)$$

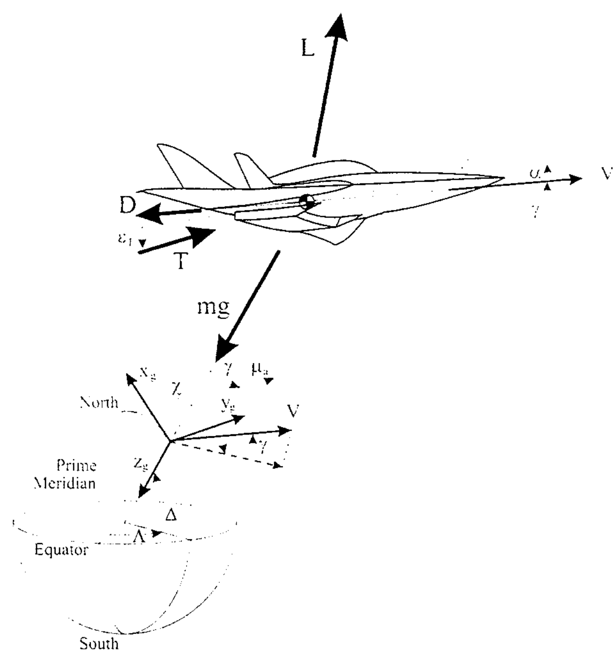

Figure 3: Forces on flight system

These equations are basically valid for the overall system as well as for the single stages.

The flight system considered in this paper is similar to the german SÄNGER-concept. The carrier and the orbital stage are winged vehicles, whereby the carrier stage is propelled by turbo-ram-jet engines and the orbital stage by rockets.

dry mass of carrier stage	149 Mg
fuel mass of carrier stage	95 Mg
mass of orbital stage	96 Mg
total mass	340 Mg

Table 2: Mass survey

Table 2 shows a mass survey of this flight system. The mass survey includes 2 Mg of the fuel consumed during taxiing before start and another 2 Mg needed for landing and taxiing after landing.

The aerothermodynamics model of the nominal flight system powered by hydrogen only may be written as:

$$\begin{aligned} L &= C_L \cdot \bar{q} \cdot S, \\ D &= C_D \cdot \bar{q} \cdot S \end{aligned} \quad (3)$$

with $C_L = C_L(\alpha, M)$ and $C_D = C_D(\alpha, \delta_e, M)$. The model of the propulsion system of the carrier stage is given by

$$T = \delta_T \cdot T^*, \quad (4)$$

$$T^* = f_\alpha(M, \alpha) \cdot T^*_{6^\circ}(M, h). \quad (5)$$

The fuel consumption model reads

$$\dot{m}_F = \phi_L \cdot b^*(M, h) \cdot T^*(M, h, \alpha). \quad (6)$$

The quantities C_L, C_D, T^* and $\dot{m}_F$ were computed from data fields to obtain smooth functions with [6].

Modelling of Drag Coefficient Changes

With regard to the effect of fuselage volume decrease on zero lift drag, the wave drag decrease is considered. An estimation is presented in the following.

In the supersonic regime C_{D0} may expressed as

$$C_{D0} = C_{DF} + C_{DW}. \quad (7)$$

The wave drag coefficient C_{DW} and the friction drag coefficient C_{DF} are assumed to be equal. Further, C_{DF} is considered as constant in regard to the fuselage volume change. The change of the wave drag coefficient C_{DW} is estimated as

$$C_{DW,new} = C_{DW,nom} \cdot \frac{V_{new}}{V_{nom}}. \quad (8)$$

With the use of this relation, a first approach for the change of the zero lift drag coefficient may be modelled as:

$$C_{D0,new} = C_{D0,nom} \cdot \left[f + (1 - f) \cdot \frac{V_{new}}{V_{nom}} \right] \quad (9)$$

with

$$f = \frac{1}{4} \cdot \{1 - \tanh[(M - 0.8) \cdot 10 - 2]\} + 0.5 \quad (10)$$

The continuous function f yields a value of about 1 for Mach numbers below 0.8 and 0.5 for higher Mach numbers. Therefore, only a change of C_{D0} for Mach numbers larger than 0.8 according to the wave drag coefficient change is obtained.

The above model for the zero lift drag coefficent change may be considered as a conservative estimation.

Optimization Problem

The major aim of trajectory optimization is to find a control law for a flight mission, which makes it possible to transfer a flight system from a starting to a final point with a minimum cost function, subject to boundary conditions and path constraints.

The controls are angle of attack α, bank angle μ_a and throttle setting δ_T.

The initial conditions for the flight system are given by the conditions of the climb at subsonic speed. They are presented in Table 3.

state variable	value at initial climb flight
h	500 m
γ	3 deg
V	150 m/s
m	338 Mg
Δ	43.5 deg
Λ	0 deg

Table 3: Initial flight conditions

The final conditions are given by the landing approach flight conditions. They are presented in Table 4.

state variable	value at landing approach
h	500 m
γ	-3 deg
V	150 m/s
m	151 Mg
Δ	43.5 deg
Λ	0 deg

Table 4: Final flight conditions

The path constraints are shown in Table 5.

The cost function is the distance between the launch site and the geographical latitude for separation. The optimization goal is to achieve a separation as far south as possible.

For solving this type of optimal control problem, efficient numerical optimization methods and computational

	minimum	maximum
α [deg]	-1.5	20
$\delta_{T,Turbo}$	0	1
$\delta_{T,Ram}$	0	$\delta_T(M, \phi_{L,max})$
$\phi_{L,max}$	$\phi_L(M, \delta_{F,min})$	3
$\bar{q}$ [kPa]	10	50
n_z	0	2

Table 5: Flight path constraints

techniques are required which are capable of coping with complex functional relationships including various kinds of constraints.

The procedure which was successfully applied in this paper is a parameterization optimization technique [10] with the graphical environment GESOP [7].

Optimization Results

The first results concern the flight path for the flight system powered only with hyrogen [3, 9]. This is used as a reference for showing the improvements of the dual-fuel configuration. Further results concern the dual-fuel concept with and without in-flight refueling.

Reference Flight Path (Fig. 4)

The reference trajectory is shown in Fig. 4. A separation point at 10.21^o northern latitude can be reached. This flight lasts 106 minutes. In Figs. 4-8 the vertical lines denote constant time intervals.

The flight consists of six different phases. The first phase is a climb with speeding up to supersonic flight. After this phase the flight system performs a level range flight with speed increase. To reach the separation configuration the flight system performs a pull up. After separation the carrier stage descends to the return flight altitude. At this altitude, a practically level range flight with speed decrease takes place. As a sixth phase the carrier stage finally performs a descent flight to the landing site.

Dual-Fuel Flight without In-Flight Refueling (Fig. 5)

The above assumption according to which the overall fuel mass is considered to be constant implies that the total fuel mass $m_{F,tot}$ is fixed ($m_{F,tot} = 95$ Mg). The mass of kerosene m_{Ker} represents an optimization parameter. The mass of liquid hydrogen can be calculated as

$$m_{LH2} = m_{F,tot} - m_{Ker}. \qquad (11)$$

For an optimal m_{Ker} of 52.0 Mg the maximum reachable latitude is 21.07^o. The reduction compared to the reference trajectory is basically due to the lower mass specific calorific value of kerosene. The flight lasts 86 minutes.

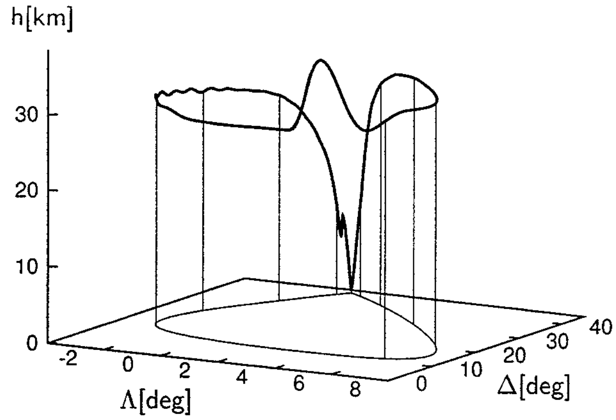

Figure 4: Reference flight path (only hydrogen fuel)

The flight path shows some similarity with the reference case, Fig. 5.

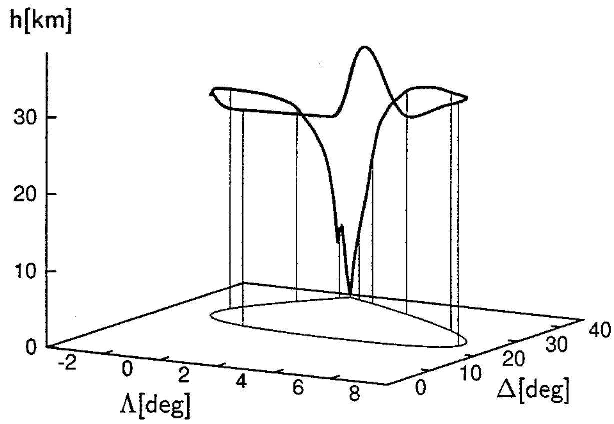

Figure 5: Dual-fuel flight path without in-flight refueling

Dual-Fuel Flight with In-Flight Refueling (Fig. 6-8)

An additional phase for in-flight refueling is now introduced. The in-flight refueling is considered to take place at a Mach number of 0.8.

Fig. 6 shows the optimized flight path for one in-flight refueling. For an optimal mass of kerosene m_{Ker} of 43.2 Mg the reachable latitude improves to 12.5^o for a flight of 160 minutes.

In the first flight phase, the system performs a subsonic range flight at an altitude of about 10 km. After in-flight refueling the flight path is basically similar to the case without refueling.

Fig. 7 shows the flight path with two in-flight refuelings. The optimal mass of kerosene is now 43.7 Mg. The reachable latitude raises to 6.5^o for a flight lasting 245 minutes.

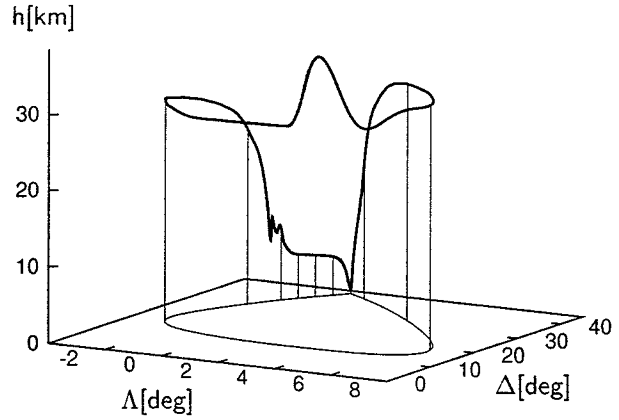

Figure 6: Dual-fuel flight path with one in-flight refueling

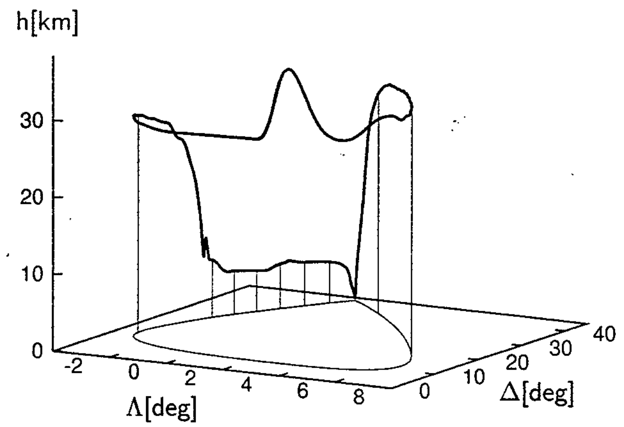

Figure 7: Dual-fuel flight path with two in-flight refuelings

The first part of the flight consists of a subsonic range flight phase and after the first refueling another subsonic range flight phase follows. After the second refueling the flight system conducts the similar flight as before without refueling.

Three in-flight refuelings make it possible to reach the equator for separation. The corresponding flight path is shown in Fig. 8. The flight lasts 323 minutes. The shape of the flight path is basically similar to that one with two in-flight refuelings, except for the third refueling process.

For comparision reasons Fig. 9 shows projections of all flights on the surface of the Earth.

To evaluate the influence of the mass of kerosene m_{Ker}, optimal flight paths for different kerosene masses were calculated. The achievable ranges are shown in Fig. 10. It turns out that the optimal mass ratio of kerosene to hydrogen for the considered flight system with in-flight refueling is about one to one.

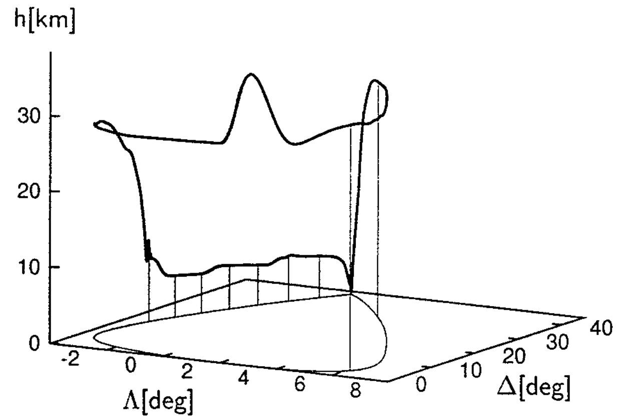

Figure 8: Dual-fuel flight path with three in-flight refuelings

Conclusions

A flexibilisation concerning the reachable orbit of a two-staged space transportation system can be achieved by enlarging the range of the carrier stage with in-flight refueling. This possibility is offered by the dual-fuel concept according to which hydrogen is used for ram jet operation and kerosene for turbo jet operation. Up to three in-flight refuelings were considered. To reach any orbit inclination three in-flight refuelings are sufficient.

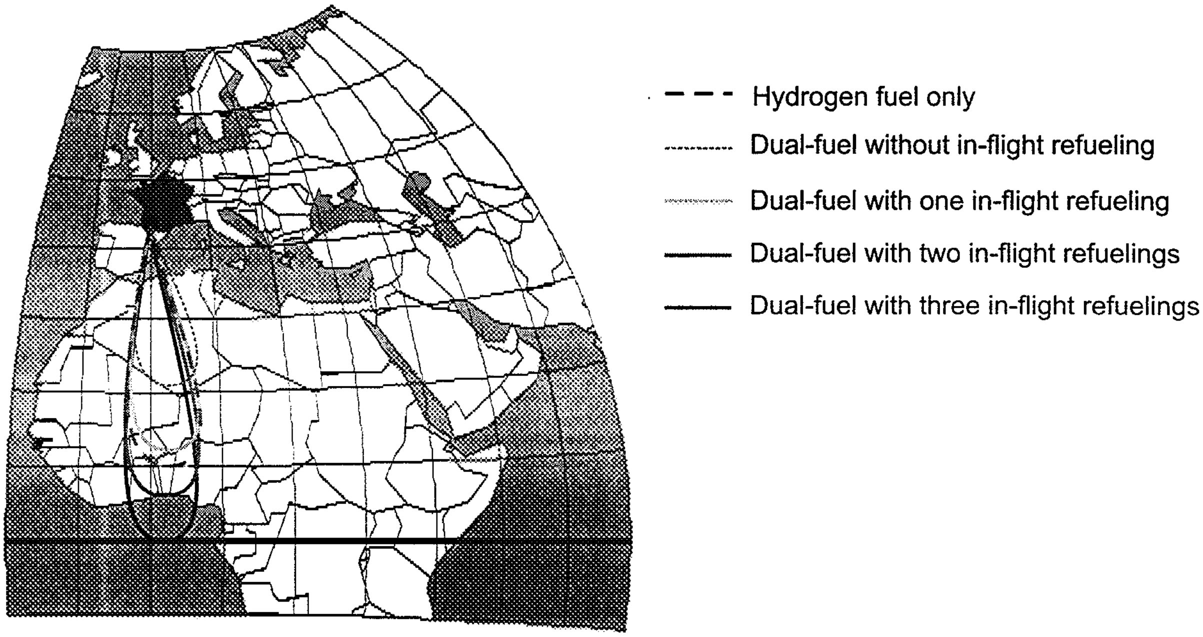

Figure 9: Projections of the trajectories

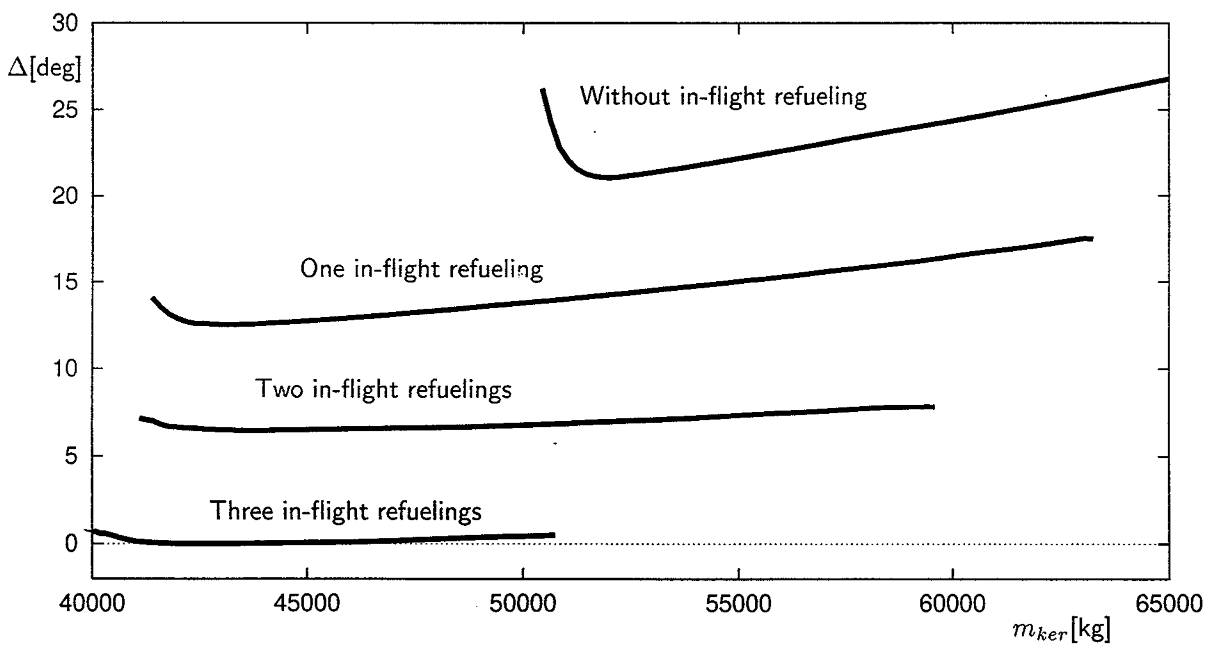

Figure 10: Reachable latitude

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