OPTIMIZATION OF A CONSTRAINED SPHERICAL LOCATION PROBLEM: THE CASE OF SIN.. (U) NORTH CAROLINA STATE UNIV AT RALEIGH DEPT OF INDUSTRIAL ENGIN... A YAMANI ET AL.
Optimization of a Constrained Spherical Locati
Problem: The Case of Single Air Craft
Mid-Air Refueling

by

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Abstract

This paper addresses the problem of a single military transport aircraft that must carry cargo from an origin base to a destination base. Refueling is required and performed by a "tanker" aircraft that originates from and returns to a third base. The objective is to determine the initial fuel required by each aircraft and the location of the refueling point so as to minimize the total fuel consumed subject to restrictions on the range of the transport and the tanker. Based on U.S. Air Force data, analytical relationships are derived which allow the problem to be formulated similar to a constrained spherical Weber problem with two main differences: (1) the objective function is non-linear, and (2) some of the constraints are a function of the decision variables. Spherical convexity of both the objective function and feasible region is shown and used to develop an optimal algorithm. Computational experience is given.
The problem addressed in this paper is that of a military transport aircraft (A/C) required to transport a cargo of w pounds from an origin base "0" to a destination base "D". The distance between these bases (D_{0D}) is greater than the range of the aircraft thus requiring it to refuel enroute. Refueling is performed in mid-air using aircraft called "tankers". The operation consists of the tanker flying from its base "B" to some point along the route of the transport A/C where it carries out the aerial refueling. Once refueling is completed the tanker returns to "B" while the transport continues on to its destination. The objective is to determine the initial fuel required by each A/C and the location of the refueling point so as to minimize the total fuel consumed by both A/C subject to restrictions on the range of the transport and the tanker. Since the distances over which the aircraft would normally fly in a real application are large, it is appropriate that the geometry of the solution approach be that of a location problem on the sphere (earth).

The closest related problem found in the literature is the spherical Weber problem with maximum distance constraints formulated by Ayken (1983). The problem consists of determining the optimal location of a source so as to minimize the sum of the weighted distance from the source to a finite number of demand points while keeping the source within a distance S. of a given point U. U. may be any of the demand points and all points are located on the surface of a sphere (earth).

The optimal solution procedure developed by Ayken was based on properties obtained by himself and others for the unconstrained version of the spherical Weber problem (Aly, Kay, and Litwhiler 1979,
Drezner 1981, Drezner and Wesolowsky 1978, Katz and Cooper 1980, Litwhiler and Aly 1979). The problem we are considering differs from the one solved by Ayken in two major considerations. First, the objective function of the problem addressed in this paper is shown to be a non-linear function of the spherical distance whereas Ayken's problem dealt with a linear objective function. Second, some of the constraints of the problem we are considering depend on some of the decision variables. These properties as well as other mathematical relationships between fuel consumption, distance traversed, cargo weight and initial fuel of the transport A/C are derived in the Appendix.

In a recent series of papers, Mehrez, Stern, and Ronen (1983), Mehrez and Stern (1985), and Melkman, Stern, and Mehrez (1986), a related problem is studied. They study the problem of refueling tankers escorting smaller aircraft with the objective of maximizing the the effective range of the smaller aircraft. A central assumption in these papers is that fuel flow is a constant. For larger cargo aircraft, this assumption is difficult to support.

Finally it should be mentioned that the initial motivation for studying the problem addressed herein resulted from various conversations between the authors and personnel at the U. S. Air Force Logistics Management Center at Gunter, AFS, Alabama. Subsequently, the Air Force provided raw data describing A/C performance at different gross weights, altitudes and speeds which was then transformed into the mathematical relationships previously mentioned. Information on these and other details related to the practical origin of this problem is also included in the Appendix.
ASSUMPTIONS AND NOTATION

Prior to formulating the problem, the following assumptions and notation need to be introduced.

**Assumptions:**

1. The gross weight of the A/C should not exceed its maximum takeoff weight (MTOW), [i.e., A/C empty weight + cargo weight + fuel weight ≤ MTOW].

2. There are no load balance or size restrictions associated with the A/C load.

3. The earth is a perfect sphere.

4. The A/C follows the great circle route (shortest path) in flying from one point to another.

5. Weather at altitude (i.e., the jet stream) is assumed to be negligible.

6. Aerial refueling takes a negligible amount of time. Thus, the region in which fuel transfer takes place is considered to be a single point.

7. Everything takes place at altitude. Thus, take-off and its cost are ignored.

**Notation:**

- **EW** = Transport A/C Empty Weight
- **MTOW** = Maximum Take-Off Weight of the transport A/C
- **F_m** = Maximum fuel capacity of the transport A/C
- **H_m** = Maximum fuel capacity of the tanker A/C
- **g** = Initial fuel of the transport A/C (a decision variable)
- **h** = Initial fuel of the tanker A/C (a decision variable)
- **w** = Cargo weight
GW = Gross weight of the transport A/C (GW = EW + g + w)

GW_{\text{max}} = Maximum allowed gross weight of the transport A/C

g_{\text{max}}(w) = The maximum fuel the transport A/C can carry in order to be able to take off with a cargo of weight w

= \min(F_{\text{max}}, MTOW - EW - w)

G_{\text{max}}(w) = The maximum fuel the transport A/C can carry when it is in the air, given that its cargo weight is w

= \min(F_{\text{max}}, GW_{\text{max}} - EW - w)

MPF(GW) = Distance traveled by an A/C in miles per 1,000 lbs of fuel at a given gross weight GW

d_{1}(B, d) = The spherical distance between the origin base (B_{1}, \delta_{1}) and the refueling point (B, d)

d_{2}(B, d) = The spherical distance between the refueling point (B, d) and the destination (B_{2}, \delta_{2})

d_{3}(B, d) = The spherical distance between the tanker base (B_{3}, \delta_{3}) and the refueling point (B, d)

R(g, w) = Range of the transport A/C when its initial fuel is g and its cargo weight is w

FC(g, w, d) = Fuel consumed by the transport A/C when it flies a distance d and its initial fuel is g and cargo weight is w

FN(w, d) = Exact amount of fuel needed by the transport A/C to fly a distance d when the cargo weighs w

[d must be \leq R(F_{\text{max}}, 0)]

R'(h, w) = Range of the tanker when its initial fuel is h and cargo weight is w (usually w = 0)
FC*(h,w,d) = Fuel consumed by the tanker when it flies a distance
d, its initial fuel is h, and cargo weight is w
[d must be \( \leq R^*(h,w) \), and usually \( w = 0 \)]

FN*(w,d) = Exact amount of fuel needed by the tanker to fly a
distance d when its cargo weight is w
[d must be \( \leq R^*(H_{max},0) \), and usually \( w = 0 \)]

\( f_1(\theta,\phi) \) = The fuel consumed by the transport A/C in flying from
(\( \theta_i,\phi_i \)) to (\( \theta,\phi \)) \( [f_1(\theta,\phi) = FC(g,w,d)] \)

\( f_m(\theta,\phi) \) = The fuel needed by the transport A/C to go from (\( \theta,\phi \))
to (\( \theta_i,\phi_i \)) \( [f_m(\theta,\phi) = FN(w,d)] \)

\( f_3(\theta,\phi) \) = The fuel consumed by the tanker in going from (\( \theta_i,\phi_i \))
to (\( \theta,\phi \)) \( [f_3(\theta,\phi) = FC'(h,0,d)] \)

\( f_n(\theta,\phi) \) = The fuel needed by the tanker to go from (\( \theta,\phi \)) back
to (\( \theta_i,\phi_i \)) \( [f_n(\theta,\phi) = FN'(0,0,d)] \)

**PROBLEM FORMULATION**

The problem can now be stated mathematically as follows:

Find \( (\theta,\phi), g \) and \( h \) that will

\( (P) \quad \text{Minimize } V(\theta,\phi) = \sum_{i=1}^{4} f_i(\theta,\phi) \)

S.T. \( d_1(\theta,\phi) \leq R[g_{m_{\phi_{\phi}}}(w),w] \) \( \quad \text{(1)} \)
\( d_2(\theta,\phi) \leq R[g_{m_{\phi_{\phi}}}(w),w] \) \( \quad \text{(2)} \)
\( d_3(\theta,\phi) \leq R^*(H_{max},0) \) \( \quad \text{(3)} \)
\( FN(w,d) \leq g \leq g_{m_{\phi_{\phi}}}(w) \) \( \quad \text{(4)} \)
\( FN^*(0,2d) \leq h \leq H_{max} \) \( \quad \text{(5)} \)

\( (h+g) \leq \sum_{i=1}^{4} f_i(\theta,\phi) \) \( \quad \text{(6)} \)
The first three constraints represent conditions that must be satisfied by the refueling point. Inequality (1) says that the distance between the origin base and the refueling point should not exceed the maximum range of the transport A/C. Inequality (2) says that the transport A/C must be able to reach its destination from the refueling point. Inequality (3) says that the tanker should be able to make a round trip safely. Constraints (4), (5) and (6) are the conditions that must be satisfied by \( g \) and \( h \), that is, \( g \) must be at least equal to the amount of fuel needed to fly from the origin to the refueling point. Similarly, \( h \) should permit the tanker to make a trip from its base to \((8,\delta)\) and back. Also, the total initial fuel for both A/C must be at least equal to the total fuel consumed.

A few more remarks are in order. First, the intersection of the first three inequality constraints (1), (2) and (3) represents a region within which all feasible refueling points must lie. Figure 1 illustrates such a region. Note that even though all feasible points are included in this region, not all the points in this region are necessarily feasible. It can be shown that any feasible point must satisfy (1), (2), (3) and the following constraint:

\[
0 \leq \theta < 2\pi
\]

\[
0 \leq \delta < \pi
\]

\[
g_m(w) = f_c(g_m(w), w, d) + \left[ H_{m} - f_c(\theta_m, 0, d) \right] \]

\[
\leq f_c(\theta, \delta) + f_c(0, \delta)
\]

which is derived from (4), (5), and (6).
Figure 1: The region inside which all feasible refueling points lie.
Second, since values of \( g \) and \( h \) greater than needed will increase fuel consumption unnecessarily, we can restrict attention to the case where the equality holds for constraint \( (\delta) \). This means that there is only one value of \( h(\theta, \delta) \) for every choice of \( g(\theta, \delta) \). Consequently, the best value of \( g(\theta, \delta) \), (denoted by \( g^*(\theta, \delta) \)) that will result in the lowest total fuel consumption for that point is the solution to the following non-linear subproblem in one dimension (\( g \)):

\[
(SP1) \quad \begin{align*}
\text{Minimize} & \quad g + FN[h_r(g), d_m] + h_r(g) \\
\text{S.T.} & \quad g_{m\text{in}}(\theta, \delta) \leq g(\theta, \delta) \leq g_{m\text{ax}}(\theta, \delta)
\end{align*}
\]

where

\[
g_{m\text{in}}(\theta, \delta) = \begin{cases} 
FN(w, d_i) & \text{if } g_r(\theta, \delta) \leq 0, \\
FN(g_r + w, d_i) + g_r & \text{if } g_r(\theta, \delta) > 0,
\end{cases}
\]

and

\[
g_r(\theta, \delta) = f_m(\theta, \delta) + f_r(\theta, \delta) - [H_{m\text{in}} - FC^s(H_{m\text{ax}}, 0, d)] \quad (13)
\]

\[
h_r(g) = f_m(\theta, \delta) + f_r(\theta, \delta) - [g(\theta, \delta) - f_r(\theta, \delta)] \quad (14)
\]

\[
h(\theta, \delta) = FN^*(h_r(g), d) + h_r(g) \quad (15)
\]

An important result due to Drezner and Wesolowsky (1978) says that the distance from a given point \( r \) within a circle of radius \( \pi/2 \) and center \( r \), is a spherically convex function. Since the right hand side of constraints (1), (2) and (3) are usually much less than \( \pi/2 \), each of these constraints represent a spherically convex set. The region resulting from their intersection will also be a spherically convex set. Therefore, Problem (P), without constraint (9), will have a spherically convex feasible region.
Our fourth remark is related to Aly et al. (1979) who showed that the search for an optimal solution to the spherical Weber problem can be restricted to the spherically convex hull of the demand points. This result can be extended to the case at hand.

**Property 1:** The search for the optimal refueling point can be restricted to the spherically convex hull of the three base points (the origin, the destination, and the tanker base).

**Proof:** Let $V$ be the spherically convex hull of the three points and $X$ be a point on the sphere such that $X \notin V$. Let $d_1$, $d_2$, $d_3$ be the spherical distance between $X$ and the origin, the destination, and the tanker base, respectively. Aly et al. (1979) proved that there exists a point $X' \in V$ that dominates $X$ in the spherical distance with respect to the three base points. That is, if $d'_1$, $d'_2$, and $d'_3$ are the distance between $X'$ and the three points, then $d'_i \leq d_i$ for $i = 1, 2, 3$. Since fuel consumption increases with distance, [i.e., $FN(.,d_1)$, $FC(.,d_2)$, $FN(.,d_3)$, and $FC(.,d_3)$ are all increasing functions of the distance], then the objective function value at $X'$ is less than or equal to the objective function value at $X$. Q.E.D.

Taking the first and fourth remarks together, it can be seen that the search for the optimal refueling point can be restricted to the intersection of the region described by $(1)$, $(2)$ and $(3)$ with the spherically convex hull of the three bases.

Finally, the fifth remark concerns the objective function. It is a nonlinear function of the spherical distance (the great circle distance). Using the fuel function (see Appendix), it is seen that
\[ f_1 = g + a'/a - [(a+a_1g)^{m} - 2a_1d_1]^{1/m} / a_1 \]

\[ f_2 = -a/a_1 + (a'' + 2a_1d'_2)^{1/m} / a_1 \]

\[ f_3 = h + a'/a_1 - [(a+a_1h)^{m} - 2a_1d_3]^{1/m} / a_1 \]

\[ f_4 = -a'/a_1 + (a'' + 2a_1d'_2)^{1/m} / a_1 \]

\[ f_5 = h+g-1/a_1 \begin{cases} [a_1g]^m - 2a_1d_1]^{1/m} - [a''+2a_1d'_2]^{1/m} \\ +[(a+a_1h)^{m} - 2a_1d_3]^{1/m} - [a''+2a_1d'_2]^{1/m} \end{cases} \]

The way the objective function is written, it is difficult to verify its spherical convexity either by using the second derivative test or by applying the definition of a spherically convex function directly. Nevertheless, spherical convexity of the objective function can be shown by rewriting the objective function using some spherically convex function like \( \text{FN}(\ldots) \). To do this, define for any point \((\theta, \phi)\) the following:

\[
\text{WFL}(g(\theta, \phi), d_1) = \text{weight of the fuel left in the transport A/C when it flies a distance } d_1 \text{ from the origin to } (\theta, \phi) \text{ given that its initial fuel is } g(\theta, \phi).
\]

Thus,

\[
\text{WFL}(g(\theta, \phi), d_1) = g(\theta, \phi) - \text{FC}[g(\theta, \phi), w, d_1] \quad (16)
\]

\( \text{WFL}(\ldots) \) is spherically convex because \( \text{FC}(\ldots, \alling) \) is spherically concave.
Note that
\[ 0 \leq WFL[g_-(\theta, \phi), d_1] \leq WFL_{max}(d_1), \]
and that \( WFL_{max}(\cdot) \) is spherically convex also.

Since \( g''(\theta, \phi) \) is the best value of \( g(\theta, \phi) \), then using the spherically convex functions \( FN \) and \( WFL \), the elements of the objective function can be rewritten as
\[
\begin{align*}
    f_1(\theta, \phi) &= FN(w + WFL[g''(\theta, \phi), d_1], d_1) \\
    f_2(\theta, \phi) &= FN(w, d_2) \\
    f_3(\theta, \phi) &= FN(0, d_3) \\
    f_4(\theta, \phi) &= FN(f_2 + f_3 - WFL[g''(\theta, \phi), d_1], d_2)
\end{align*}
\]

and the total fuel consumption \( V(\theta, \phi) = \sum_{i=1}^{4} f_i(\theta, \phi) \).

Both \( FN(\cdot, \cdot) \) and \( FN''(\cdot, \cdot) \) are convex and increasing functions of their arguments, which, in turn, are spherically convex functions. Therefore, the resulting objective function is spherically convex (Greenberg and Pierskalla 1971, Rockafellar 1970).

**Motivation for the solution procedure of (P0)**

For this problem, the optimal point \((\theta^*, \phi^*)\) and its optimal \( g''(\theta^*, \phi^*) \) (and consequently, its optimal \( h''(\theta^*, \phi^*) \)) are to be found. Since \( g''(\theta^*, \phi^*) \) depends upon \((\theta, \phi)\) and we do not know this in advance (note that (Sp1) needs to be solved to find this out!), it is difficult to use (19), (20), (21) and (22) directly. That is, we cannot search for both \((\theta^*, \phi^*)\) and \( g''(\theta^*, \phi^*) \) simultaneously. However, this difficulty can be overcome by creating an upper bound function that can be improved from one iteration to another until its minimum value coincides with the minimum of the original function. To illustrate this, let
\[ a(B, d) = \frac{WFL[g(B, d), d_1]}{WFL_{max}(d_1)} \]  

then,

\[ 0 \leq a(B, d) \leq 1 \text{ for all } (B, d) \]  

Thus, \( g^*(B, d) \) would result in \( a^*(B, d) \), where \( a^*(B, d) \) is the best value of \( a(B, d) \), i.e.,

\[ a^*(B, d) = \frac{WFL[g^*(B, d), d_1]}{WFL_{max}(d_1)} \]  

Also, from (25), we have

\[ WFL[g(B, d), d_1] = a(B, d)WFL_{max}(d_1) \]  

The elements of the objective function can be rewritten using

\[ a^*(B, d)WFL_{max}(d_1) \]  

instead of \( WFL[g^*(B, d), d_1] \) as

\[
\begin{align*}
    f_1(B, d) &= FN[w + a^*(B, d)WFL_{max}(d_1), d_1] \\
    f_2(B, d) &= FN(w, d_1) \\
    f_3(B, d) &= FN^*(0, d_1) \\
    f_4(B, d) &= FN^*[f_n + f_{n-1} - a^*(B, d)WFL_{max}(d_1), d_1] \\
\end{align*}
\]

Now setting \( a(B, d) = a \) for all points, and denoting the resulting function by \( UB(B, d, a) \), one gets

\[
\begin{align*}
    f_1'(B, d) &= FN[w + aWFL_{max}(d_1), d_1] \\
    f_2'(B, d) &= f_2(B, d) = FN(w, d_1) \\
    f_3'(B, d) &= f_3(B, d) = FN^*(0, d_1) \\
    f_4'(B, d) &= FN^*[f_n + f_{n-1} - aWFL_{max}(d_1), d_1] \\
\end{align*}
\]

where \( 0 \leq a \leq 1 \)

and \( UB(B, d, a) = \sum_{i=1}^{4} f_i'(B, d) \)  

\( UB(B, d, a) \) has the following characteristics:

1) It is spherically convex because it is the sum of spherically convex functions;

2) \( UB(B, d, a) \geq V(B, d) \)

In other words, since any \( g \) other than \( g^*(B, d) \) would result in a
higher cost for \( V(\theta, \delta) \), and also produce an "\( a \)" that is different from \( a^*(\theta, \delta) \), then any "\( a \)" used in \( UB(\theta, \delta, a) \) would make \( UB(\theta, \delta, a) \leq V(\theta, \delta) \). Therefore UB is an upper-bound for the objective function:

3) \( UB(\theta, \delta, a^*(\theta, \delta)) = V(\theta, \delta) \) for any \((\theta, \delta)\). That is, the equal sign of eq. (32) holds true when \( a = a^*(\theta, \delta) \).

Therefore

\[
UB(\theta^*, \delta^*, a^*(\theta^*, \delta^*)) = V(\theta^*, \delta^*)
\]  

(33)

4) \( UB(\theta, \delta, a) = V(\theta, \delta) \) at the boundary points where \( d_1(\theta, \delta) = R(g_{\max}(w), w) \) because, at those points, \( WFL_{\max}(d_1) = 0 \). Thus the value of \( a \) does not matter.

How can we use this UB function to solve \((P)\)? Given a particular value of \( a \), we can optimize the UB function to find the best \((\theta, \delta)\) that corresponds to it. Now, if at some iteration, we have the value of \( a^*(\theta^*, \delta^*) \) [without knowing \((\theta^*, \delta^*)\)], and we optimize the UB function, then we will end up with \((\theta^*, \delta^*)\). This is true since if \((\theta^*, \delta^*)\) minimizes the true objective function, it will also minimize \( UB(\theta, \delta, a^*(\theta^*, \delta^*)) \).

**SOLUTION PROCEDURE OF (P)**

1. **Initialization:**

   Let \( k=0 \), and \( a^* = 1 \). Start with a point \((\theta^0, \delta^0)\) that satisfies (1), (2) and (3) [(See Yamani 1986 for the selection of a good starting point).]

2. **Let** \( k=k+1 \). Find the point that will minimize \( UB(\theta, \delta, a^{k-1}) \) s.t. (1), (2), and (3). Let the solution be \((\theta^k, \delta^k)\).

3. For \((\theta^k, \delta^k)\), solve (SP1) to find the best \( g^*(\theta^k, \delta^k) \). Use
equation (25) to find $a^*(\theta^k, \phi^k)$.

4. If $a^*(\theta^k, \phi^k) \neq a^{k-1}$, we have an improvement in the objective function. Therefore, let $a^k = a^*(\theta^k, \phi^k)$ and go to step 2.

Otherwise, the solution is $(\theta^k, \phi^k)$, $g^*(\theta^k, \phi^k)$, and $h^*(\theta^k, \phi^k)$ is calculated from eqs. (14) and (15).

Convergence Proof

We need to show that

$$\sum_{i=1}^{\Delta} f_i(\theta^{k-1}, \phi^{k-1}) \geq \sum_{i=1}^{\Delta} f_i(\theta^k, \phi^k)$$

(34)

Assume, at iteration $k-1$, that

$$a^*(\theta^{k-1}, \phi^{k-1}) \neq a^{k-2}.$$  

(Otherwise, we would have stopped there.)

By setting $a^{k-1} = a^*(\theta^{k-1}, \phi^{k-1})$, we have

$$\sum_{i=1}^{\Delta} f_i(\theta^{k-1}, \phi^{k-1}) = UB(\theta^{k-1}, \phi^{k-1}, a^{k-1})$$

(35)

At iteration $k$, since $(\theta^k, \phi^k)$ minimizes $UB(\theta, \phi, a^k)$,

$$UB(\theta^{k-1}, \phi^{k-1}, a^{k-1}) \geq UB(\theta^k, \phi^k, a^{k-1})$$

(36)

But,

$$UB(\theta^k, \phi^k, a^{k-1}) \geq \sum_{i=1}^{\Delta} f_i(\theta^k, \phi^k)$$

(37)

and inequality (34) follows.

Moreover,

$$\sum_{i=1}^{\Delta} f_i(\theta^{k-1}, \phi^{k-1}) \geq \sum_{i=1}^{\Delta} f_i(\theta^k, \phi^k)$$

(38)

if $$UB(\theta^k, \phi^k, a^{k-1}) \geq \sum_{i=1}^{\Delta} f_i(\theta^k, \phi^k).$$

(39)

The last inequality holds true if $a^*(\theta^k, \phi^k) \neq a^{k-1}$. Therefore, the true objective function improves from one iteration to another.

Since the problem is spherically convex, the solution procedure will converge to the global optimum solution (Drezner and Wesolowsky.
Numerical Results
The above procedure was programmed on a Vax 11/750 in BASIC. There was no attempt at program efficiency. Several test problems were solved to represent a variety of possible geographic configurations and complexities. The minimum CPU time was approximately 0.5 second (2 iterations) and the maximum was almost 1.0 second (4 iterations) for convergence within one degree longitude and latitude. Convergence within one minute longitude and latitude required only one more iteration in each case with a maximum CPU time of 1.3 seconds. The results of these test problems are summarized in Table 2, with Table 1 providing a key for understanding the entries in Table 2.

Summary
In this paper we have shown that the single aircraft refueling problem is a non-linear convex location problem on the sphere. The algorithm that has been presented is an optimal solution procedure for this problem. In the sequel to this paper, these results are used as the basis for solving the more complex multi-aircraft refueling problem.
TABLE 1: Key for trial runs chart of Table 2

<table>
<thead>
<tr>
<th>Location</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Jersey</td>
<td>75W</td>
<td>40N</td>
<td>A</td>
</tr>
<tr>
<td>Delaware</td>
<td>75W</td>
<td>38N</td>
<td>B</td>
</tr>
<tr>
<td>North Carolina</td>
<td>78W</td>
<td>35N</td>
<td>C</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>66W</td>
<td>18N</td>
<td>D</td>
</tr>
<tr>
<td>Azores Islands</td>
<td>25W</td>
<td>37N</td>
<td>E</td>
</tr>
<tr>
<td>Iceland</td>
<td>20W</td>
<td>65N</td>
<td>F</td>
</tr>
<tr>
<td>Germany</td>
<td>10E</td>
<td>50N</td>
<td>G</td>
</tr>
<tr>
<td>Turkey</td>
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<td>J</td>
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<tr>
<td>England</td>
<td>0E/W</td>
<td>52N</td>
<td>K</td>
</tr>
</tbody>
</table>

**W = Cargo Weight**

- 100,000 lbs: 1
- 200,000 lbs: 2

**Fuel ACCR = Fuel Accuracy**

10 means to within 10 lbs

**POS ACCR = Position Accuracy**

1 means to within 1 degree
Table 2: Trial runs for Test Problem

| Run No. | "O" | "D" | "B" | Initial Refueling Point (Guess) | Fuel W A CCR | Pos A CCR | \( E_0 \) (lbs) | Fuel Transferred to Transport (lbs) | Fuel Consumed By Tanker (lbs) | Total Fuel (lbs) | Optimal Location | Time (Sec) | Iterations |
|---------|-----|-----|-----|---------------------------------|--------------|-----------|---------------|------------------------------------|-----------------|----------------|-------------|------------|
| 1       | A   | H   | D   | 40W 35N                         | 2            | 10        | 1             | 113,521                            | 136,704         | 149,055        | 399,280     | 49W 40N    | 0.6         | 2          |
| 2       | G   | C   | F   | 35W 40N                         | 2            | 10        | 1             | 79,431                             | 130,541         | 1,058          | 211,030     | 20W 65N    | 1.0         | 4          |
| 3       | B   | I   | E   | 30W 30N                         | 1            | 10        | 1             | 137,142                            | 144,464         | 5,866          | 287,472     | 25W 37N    | 0.8         | 2          |
| 4       | B   | J   | D   | 30W 25N                         | 2            | 10        | 1             | 118,712                            | 152,613         | 156,783        | 428,008     | 42W 36N    | 0.5         | 2          |
| 5       | C   | K   | F   | 30W 50N                         | 2            | 10        | 1             | 129,882                            | 54,425          | 19,269         | 203,576     | 29W 63N    | 0.6         | 2          |

"O" = Origin

"D" = Destination

"B" = Tanker Base

\( E_0 \) = Initial fuel for transport A/C

\( h_0 \) = Initial fuel for tanker A/C

Fuel consumed by tanker + fuel transferred to transport
Appendix A

Derivation and Characterization of the Fuel Consumption Function and Other Related Functions

Here, mathematical representation of the various relationships between fuel consumption, distance traveled, cargo weight, and initial fuel of a typical jet A/C are derived.

The United States Air Force provided raw data describing A/C performance at different gross weights, different altitudes, and different speeds. These raw data have to be transformed before they are useful. A sample of these data is shown in Figure 2 for a C-5A transport A/C flying at an altitude of 31,000 feet. Different curves are presented for different A/C weights, and they show the distance traveled per 1,000 pounds of fuel burned at a given speed and at that given gross weight (GW). Consider the points on the curve indicating 99 percent maximum specific range. It is assumed, without loss of generality, that the transport A/C will operate at those points since speed is maximized, while fuel consumption is only 1 percent greater than the minimum possible.

The distance traveled in miles per 1,000 pounds of fuel burned when the A/C gross weight is GW, denoted here as MPF(GW), is plotted against gross weight GW in Figure 3 using the 99 percent line in Figure 2. Least square linear and quadratic fits to the data were tried, and both fit well as seen in Figure 3.

For the linear fit,

\[ MPF(GW) = a_0 + a_1GW, \]

where

\[ a_0 = 36.2829, a_1 = -0.027 \]
Model C-5A

SPECIFIC RANGE

4 Engines 31,000 Feet

Figure 2: Data for C-5A aircraft.
$MPF(GW) = \text{Miles per 1000 lbs. of fuel burned for a given gross weight}$

GW = Gross weight in 1000 lbs.

Figure The MPF function versus GW.
and correlation coefficient = -0.9919.

For the quadratic fit,

$$MPF(GW) = b_0 + b_1GW + b_2GW^2$$

where

$$b_0 = 43.7616, b_1 = -0.0576, b_2 = 2.94 \times 10^{-6}$$

and correlation coefficient = -0.9983.

Only the linear form of the function will be used here. The use of the quadratic form is similar (Yamani 1986).

Note that at any moment during the flight,

$$GW = EW + w + f$$

where $f$ = the present (instantaneous) amount of fuel and $EW = A/C$ empty weight. During flight, $f$ changes due to fuel burning; thus, $GW$ changes while $EW$ and $w$ stay the same. So,

$$dGW = df$$

**The Range Function** $R(g,w)$

Initial Gross Weight = $EW + w + g$

Final Gross Weight = $EW + w$

Then,

$$R(g,w) = \left. \frac{EW+w+g}{EW+w} \right\vert_{MPF(GW)} dGW$$

$$= \left. g \right\vert_{0}^{g} \int_{0}^{g} MPF(GW) df$$

$$= \left. g \right\vert_{0}^{g} \int_{0}^{g} MPF(EW+w+f) df$$

**The Fuel Consumption Function** $FC(g,w,d)$

Let $g_r$ equal the final amount of fuel left.

Then,

$$FC(g,w,d) = g - g_r$$

Thus, finding $FC$ reduces to finding $g_r$, which can be accomplished
by solving for $g_r$ in the following equation:

$$d = \frac{g}{g_r} \int_{g_r}^{\text{MPF}(E+W+f)} df$$
$$d = \frac{g}{g_r} \int [a_0 + a_1(E+W)] df$$

which results in

$$g_r = -a/a_1 + [(a+a_1g)^{2a_1} - 2a_1d]^{1/n} / a_1$$

Thus,

$$F_C(g,w,d) = g + a/a_1 - [(a+a_1g)^{2a_1} - 2a_1d]^{1/n} / a_1$$

where

$$a = a_0 + a_1(E+W)$$

The Fuel Requirement Function $FN(w,d)$

If the distance $d$ to be flown and the cargo weight $w$ are known in advance, then the amount of initial fuel $g$ must be at least as great as the amount of fuel needed. If $g$ is set equal to $FN(w,d)$, then we can use the range function $R(g,w)$ to solve for $g$. That is, set

$$R(g,w) = d = [a' + a_1w + (a_1/2)g]g,$$

where

$$a' = a_0 + a_1E$$

Solving for $g$ results in the following equation:

$$FN(w,d) = g = -w/a' + [(a'+a_1w)^n + 2a_1d]^{1/n} / a_1$$

Table 3 summarizes the various fuel functions.
TABLE 3: Summary of the fuel-related functions

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Function Value Using a Linear Fit for MPF</th>
<th>Function Value Using a Quadratic Fit for MPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPF(GW)</td>
<td>$a_o + a_1 GW$</td>
<td>$b_o + b_1 GW + b_2 GW^2$</td>
</tr>
<tr>
<td>$R(g_o, w_o)$ - Range</td>
<td>$a'_o + a_1 w_o + \frac{a_1}{2} g_o g_o$</td>
<td>$b'_o + b_1 w_o + b_2 w_o + \left( b_2 w_o + \frac{b_1}{2} \right) g_o$ + $b_2 g_o^2 g_o$</td>
</tr>
<tr>
<td>$FC(g_o, w_o, d)$ - Fuel Consumed</td>
<td>$g_o + \frac{a}{a_1} - \frac{\sqrt{(a + a_1 g_o)^2 - 2a_1 d}}{a_1}$</td>
<td>(Roots of a cubic equation) See Yamani (1986)</td>
</tr>
<tr>
<td>$FN(w_o, d)$ - Fuel needed</td>
<td>$-w_o - \frac{a'_o}{a_1} + \frac{\sqrt{(a'_o + a_1 w_o)^2 + 2a_1 d}}{a_1}$</td>
<td>(Roots of a cubic equation) See Yamani (1986)</td>
</tr>
</tbody>
</table>

$a'_o = a_o + a_1 EW$

$b'_o = b_o + b_1 EW + b_2 EW^2$

$a = a_o + a_1 (EW + w_o) = a'_o + a_1 w_o$

$b'_1 = b_1 + 2b_2 EW$
Characteristics of the fuel functions

(1) The function $F_N(w,d)$ is a strictly convex and increasing function of the distance $d$ for any given value of the cargo weight $w$. This can be shown by taking the first and second derivatives of $F_N$ with respect to $d$.

\[
\frac{dF_N}{dd} = \frac{1}{[(a'+a_1w)^m + 2a_1d]^{1/m}} > 0
\]
\[
\frac{d^2F_N}{dd^2} = -\frac{a_1}{[(a'+a_1w)^m + 2a_1d]^{2/m}} > 0
\]

because $a_1 < 0$. Therefore, $F_N$ is strictly convex in $d$. Moreover, since the first derivative is always positive, $F_N$ is an increasing function of $d$.

(2) The function $F_N$ is a strictly convex and increasing function of the cargo weight $w$ for any given value of $d$. This can be shown in a straightforward fashion as in the previous case. Yamani (1986) proved that if the distance $d$ is measured along the surface of a sphere (earth), then the function $F_N(w,d)$ is spherically convex (s-convex) over a spherical disc of radius $\pi/4$.

(3) The function $F_C(g,w,d)$ is a concave and increasing function of the distance $d$ for any given values of the initial fuel $g$ and the cargo weight $w$.

(4) The function $F_C(g,w,d)$ is a convex and increasing function of $w$ for any given values of $g$ and $d$.

Again, both cases (3) and (4) can be shown to be true in a fashion similar to that of $F_N(w,d)$. 
References


