

A satellite-style map of Antarctica, showing the continent in white and yellow, surrounded by the dark blue ocean. The map is centered on the South Pole.

Fuel-cache site-selection for polar research: A Summary of Results

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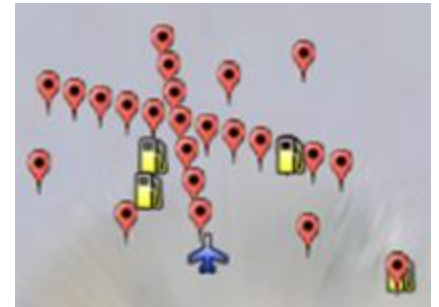
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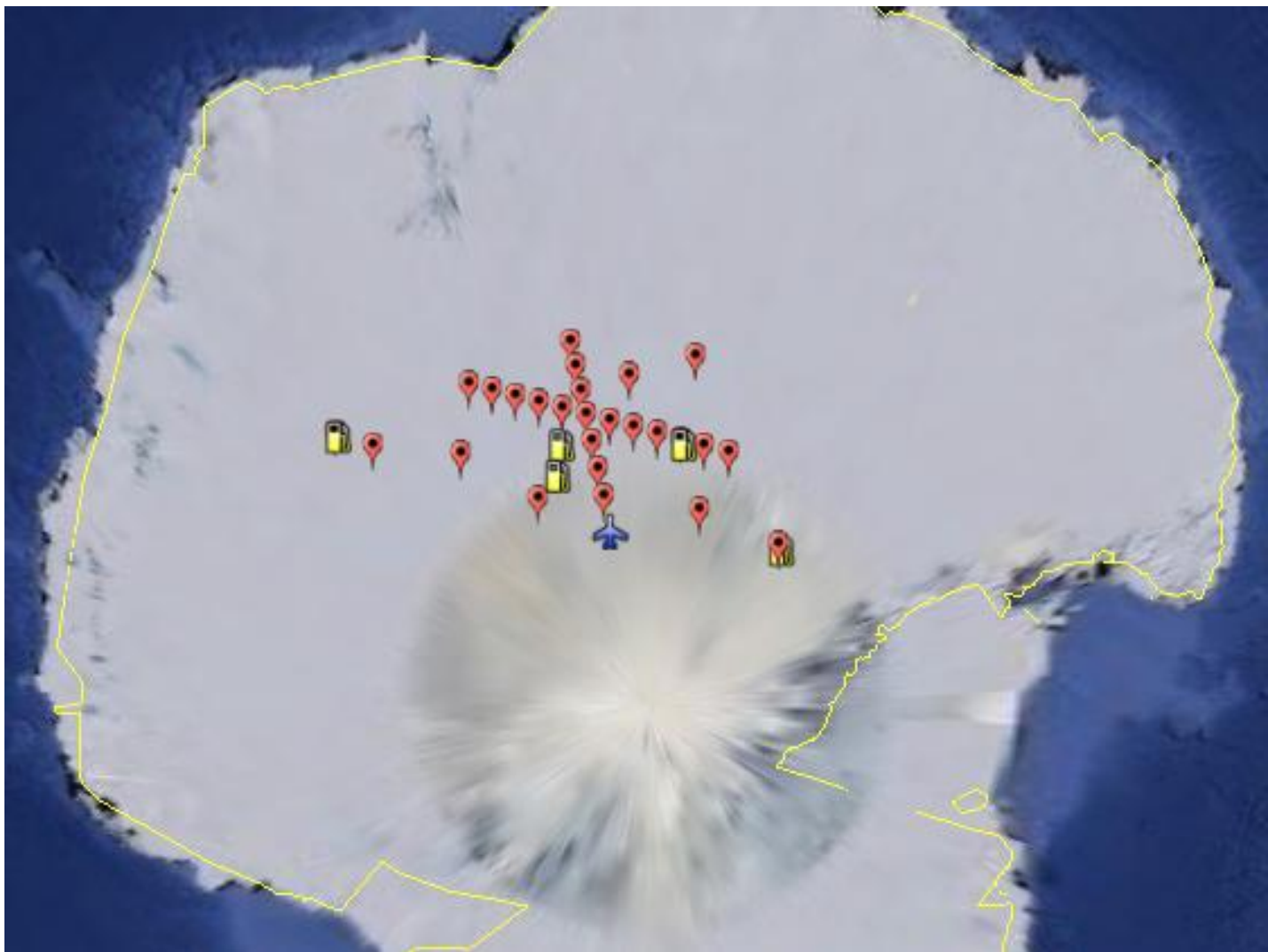
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Introduction

- Antarctic Geospatial Information Center (AGIC)
- Fly to locations around home base to install and maintain research equipment
- Flights can not be combined
- Some flights require refueling in the field at fuel cache sites



Fuel Cache Site Selection



Contrasting FCSS Routing with Traveling Salesman Problem

TSP

- Single route to many points
- Route must include all destination points

FCSS

- Individual routes from home to each point
- Each route can only include one destination point because scientists must spend a full day there and then return

Other problems with similar characteristics

- Installation task where vehicle can carry the materials for only one installation at a time.
- Research task where the tools needed are very specific to the particular task and not all tools can be carried at once.
- Transportation task where vehicle capacity is limited to the items for one customer.

Problem Definition

- **Given**

- Research points $R = \{r_1, \dots, r_n\}$
- Origin of research flights $\{h\}$
- Possible fuel cache sites $C = \{c_1, \dots, c_m\}$
- Aircraft characteristics
 - fuel tank capacity, fuel safety margin, operational weight
 - Fuel consumption model
- Payload

- **Find**

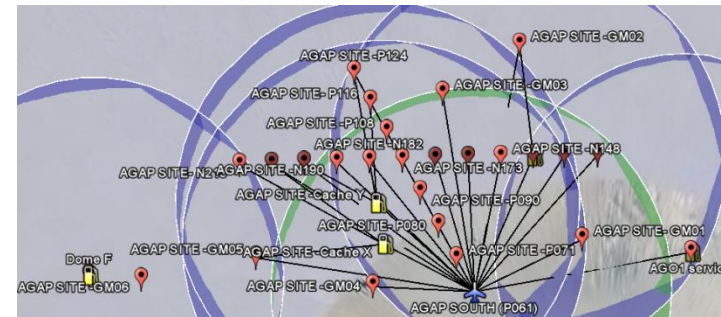
- Feasible path for each r_i in R from h to r_i and back to h .
- Amount of fuel to place at each cache
- The number of refueling flights to each cache

- **Objective**

- Minimize fuel consumed by research and refueling flights

- **Constraints**

- Capacity of cache sites is assumed infinite.
- Cache set C is static
- All fuel taken from c_i in C must be flown via refueling flights.
- A flight is either for placing fuel or visiting a research point, not both.
- The feasible path contains at most one stop to refuel at a site en route from h to r_i and at most one stop to refuel at en route from r_i to h and contains one research point.



More definitions

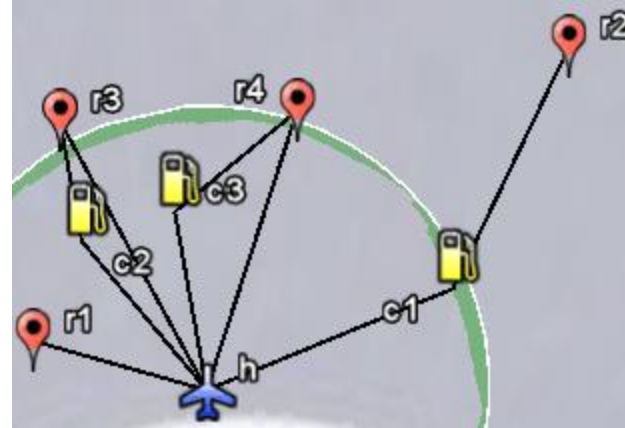
- $fuelCost(h,p)$ – fuel cost for round trip flight from h to p
- $fuelCost(h,r,c)$ – fuel cost for round trip flight from h to r using cache site c to refuel
- $refuelCost(h, r, c)$ – cost to place enough fuel at c to support a round trip flight to r that uses c to refuel.

For example: if the flight to r need 1000 lbs of fuel from the c , maximum payload of a flight to c is 800 lbs, then

$$refuelCost(h, r, c) = 2 \times fuelCost(h,c)$$

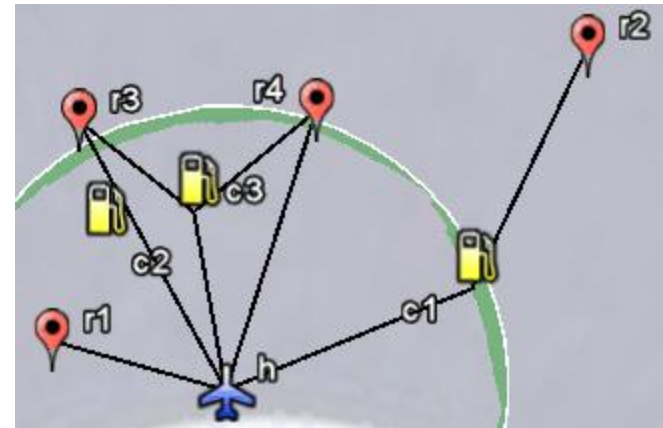
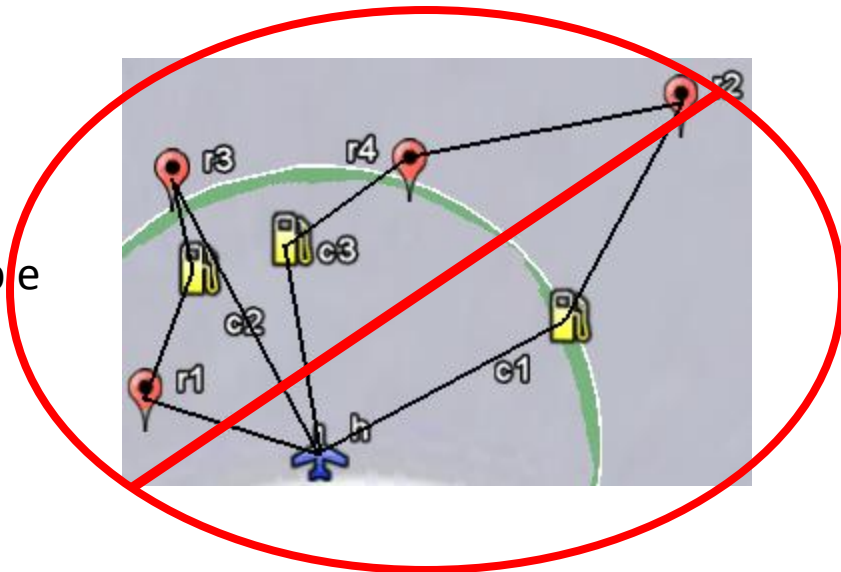
Example

Problem



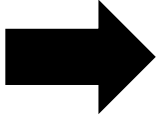
Possible Solutions

Infeasible

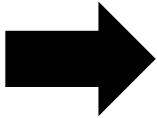


Optimal Solution

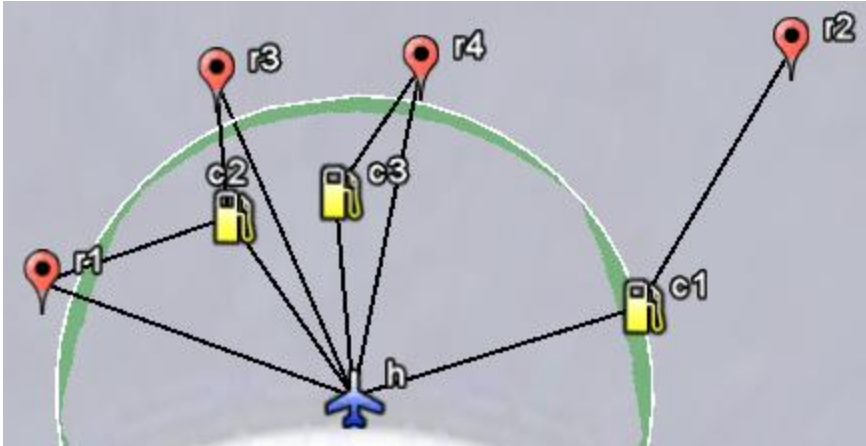
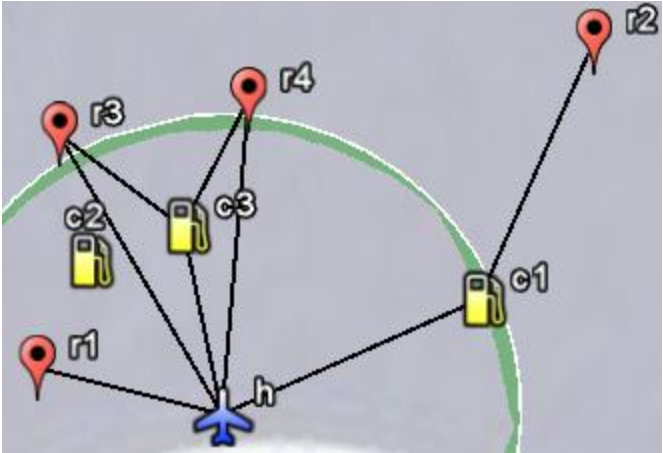
Why is it hard?



Change r1 location slightly

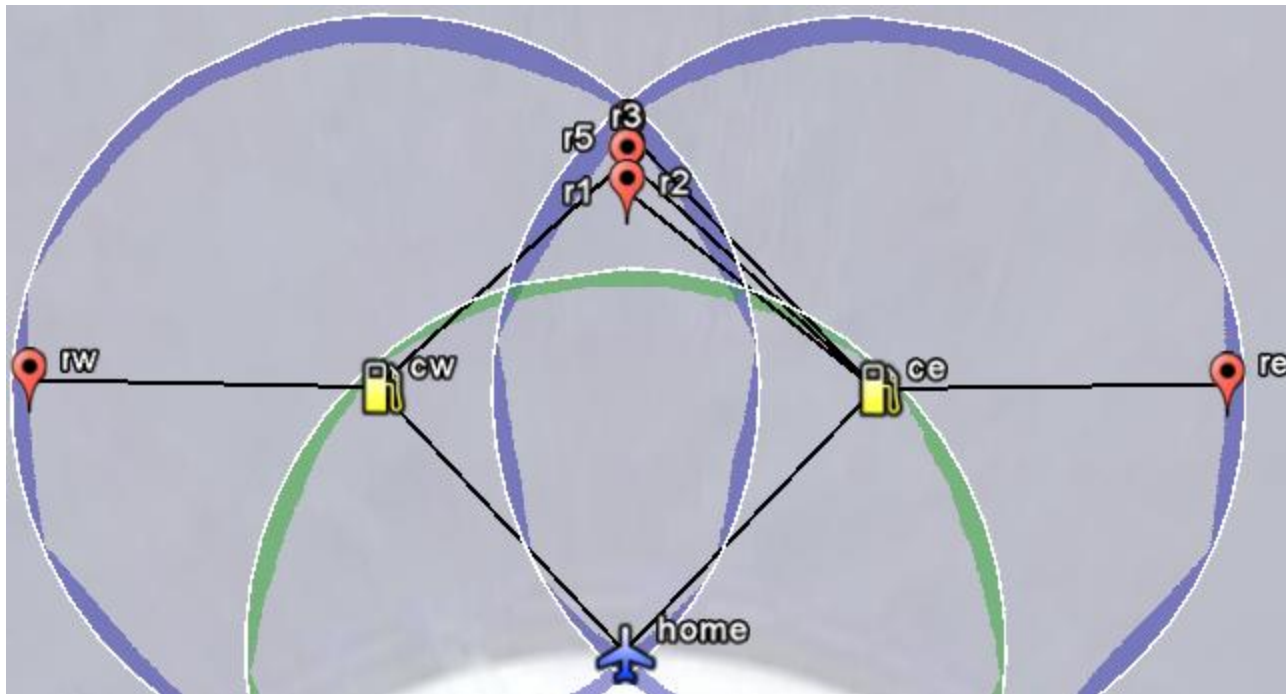


Change r3 assignment



Why is it hard?

- At least as hard as PARTITION [Karp, 1972].
- PARTITION is a special case



Related Work

- Current method: Manually create flight plans with Excel spreadsheet for fuel consumption calculations

Site	#s Fuel reqd from AGAP South	One way Distance (nm) from AGAP S	Roundtrip Distance (nm) w/refuel stop	Total Flight Time (FT)	Install or Service site?	Estimated Ground Time (GT)	Total FT and GT	Refuel stop required?	Refuel site	# drums needed at refuel site	Max ACL	Ability to combine with other site?
AGO1	1350	309	619	4	Service	4.5	8.5	YES	AGO 1	3	1975	YES
N124	1350	252	1000	6.5	Service	4.5	11.0	YES	AGO 1	8	1500	? (duty day)
N140 (AGO 4)	1000	201	402	2.6	Service	4.5	7.1	YES	AGO 4	2	2300	YES
N132	1000	222	488	3.1	Install	3.5	6.6	YES	AGO 4	3	2300	Possibly
GM02	1000	343	710	4.6	Install	3.5	8.1	YES	AGO 4	6	1800	Possibly
GM03	1000	273	702	4.5	Install	3.5	8.0	YES	AGO 4	6	1800	Possibly
GM06	2300	461	1230	7.9	Install	3.5	11.4	YES	Dome F	8	1000	NO (ACL & duty day)
GM07 (Dome F)	2300	538	1076	6.9	Install	3.5	10.4	YES	Dome F	6	1000	NO (ACL & duty day)
GM01	800	164	329	4.2	Service	4.5	8.7	NO	-	-	1750	? (duty day)
GM04	700	139	277	1.8	Service	4.5	6.3	NO	-	-	1950	YES
N148	900	186	372	2.4	Install	3.5	5.9	NO	-	-	1500	? (ACL)
N156	900	183	363	2.3	Service	4.5	6.8	NO	-	-	1600	YES
N165	900	188	376	2.4	Install	3.5	5.9	NO	-	-	1550	YES
P071	350	52	103	0.7	Install	3.5	4.2	NO	-	-	2600	YES
P080	550	102	205	1.3	Service	4.5	5.8	NO	-	-	2200	YES
P090	750	154	308	2.0	Install	3.5	5.5	NO	-	-	1800	YES
N173	950	204	408	2.6	Service	4.5	7.1	NO	-	-	1400	? (ACL)
N182	850	228	474	3.1	Install	3.5	6.6	YES	Cache Y	3	2400	YES
P116	850	294	634	4.1	Install	3.5	7.6	YES	Cache Y	5	1900	? (duty day)
P124	850	340	720	4.6	Install	3.5	8.1	YES	Cache Y	6	1600	? (duty day)
N190	850	290	514	3.3	Install	3.5	6.8	YES	Cache Y	4	2400	YES
N198	850	290	585	3.8	Service	4.5	8.3	YES	Cache Y	4	2100	? (duty day)
N206	850	326	665	4.3	Install	3.5	7.8	YES	Cache Y	5	1800	? (duty day)
N215	850	364	749	4.8	Install	3.5	8.3	YES	Cache Y	6	1500	? (duty day)
GM05	850	302	722	4.7	Install	3.5	8.2	YES	Cache Y	6	1600	? (duty day)
P061 (AGAP S)	-	-	-	-	Service	4.5	-	-	-	-	-	-

Manual Process

- Step 1: Determine which research points need a refuel stop
- Step 2: Choose cache sites for each research point
- Step 3: Determine the amount of fuel to place at each cache site to support the refueling
- Step 4: Identify opportunities to consolidate fuel placement efforts by changing cache selections
- Step 5: Recalculate fuel placement flights

Related work

Routing
with refuel
sites

Cost of
fuel is
constant

**Cost of fuel
depends on
others using
sites**

Multi-depot
(cache site)
customer
allocation

Assume
customer
demand is
independent
of depot
(cache site)
assignment

**Customer
demand
varies based
on depot
(cache site)
assignment**

Contribution

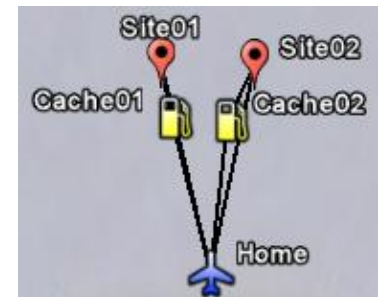
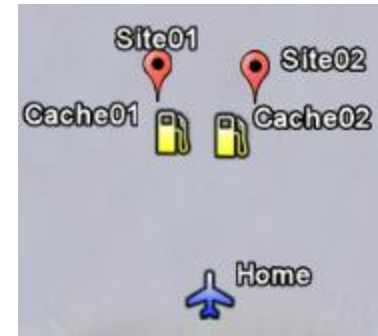
- Two heuristics and an algorithm
 - Research Flight Cost Only
 - Optimize fuel consumption research flights only
 - Not globally optimal, but guarantees feasibility
 - Independent Refueling Flights
 - Optimize fuel consumption assuming refueling flights are not consolidated.
 - Filter and Refine
 - Global optimal
 - Uses Independent Refueling Flights to seed and bound solution

Example



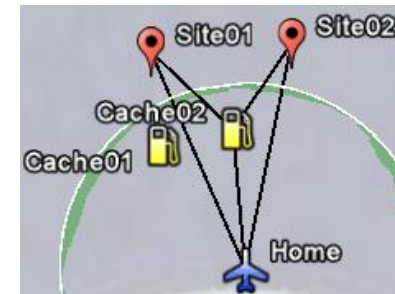
Contribution – Research Flights Only

```
ResearchFlightsOnly {  
  foreach  $r_i$  in  $\{r_1, \dots, r_n\}$  {  
    minFuelCost  $\leftarrow \infty$ ;  
    cacheSiteAssignment[ $r_i$ ]  $\leftarrow$  null;  
    foreach  $c_j$  in  $\{c_1, \dots, c_m\}$  {  
      if(fuelCost(h,  $r_i$ ,  $c_j$ ) < minFuelCost) {  
        minFuelCost = fuelCost(h,  $r_i$ ,  $c_j$ );  
        cacheSiteAssignment [ $r_i$ ] =  $c_j$ ;  
      }  
    }  
  }  
  return cacheSiteAssignment[];  
}
```



Contribution – Independent Refueling Flights

```
IndependentRefuelingFlights {  
  foreach  $r_i$  in  $\{r_1, \dots, r_n\}$  {  
    minFuelCostIncludingRefueling  $\leftarrow \infty$ ;  
    cacheSiteAssignment[ $r_i$ ]  $\leftarrow$  null;  
    foreach  $c_j$  in  $\{c_1, \dots, c_m\}$  {  
      if(fuelCost(h,  $r_i, c_j$ ) + refuelingCost(h,  $r_i, c_j$ ) <  
        minFuelCostIncludingRefueling) {  
        minFuelCostIncludingRefueling = fuelCost(h,  $r_i, c_j$ ) +  
          refuelingCost(h,  $r_i, c_j$ );  
        cacheSiteAssignment [ $r_i$ ] =  $c_j$ ;  
      }  
    }  
  }  
  return cacheSiteAssignment[];  
}
```



Can we do better?

- Each cache used in solution requires at least one refueling flight.
 - Fewer caches used => fewer refueling flights



Contribution – Filter and Refine

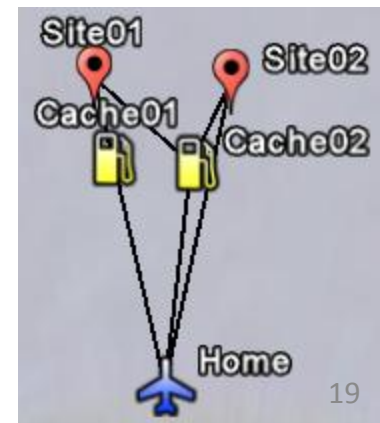
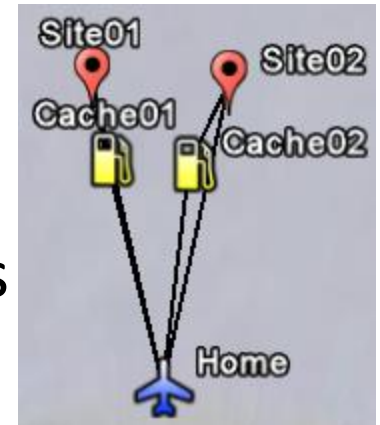
- Step 1: execute Independent Refueling Flights
- Step 2: Upper bound cost to visit each research point:

$$upperBound(r_i) = fuelCost(h, r_i, c_{i_0}) + refuelCost(h, r_i, c_{i_0})$$

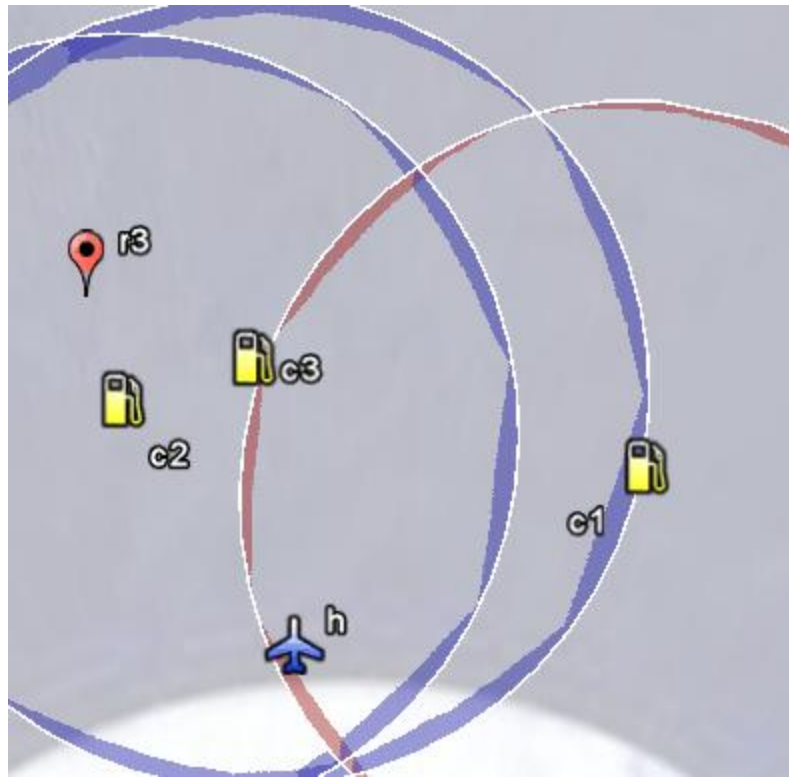
- Step 3: For each $\{r_1, \dots, r_n\}$, remove caches from consideration where:

$$upperBound(r_i) > fuelCost(h, r_i, c_j) + refuelCost(h, r_i, c_j) - fuelCost(h, c_j)$$

- Step 4: Try all combinations calculating total consumption including refueling flights



Example: Remove infeasible caches

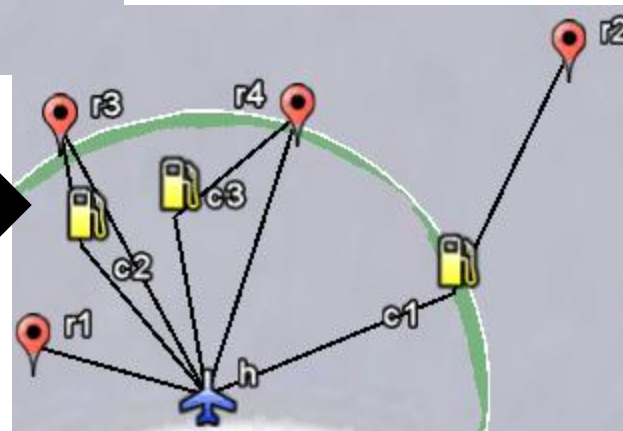
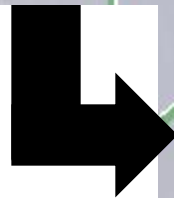


r3 is unreachable from c1 due to aircraft max fuel capacity
=> do not include c1 in search

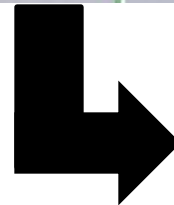
Example: Filter with bound (r4)



Initial Points

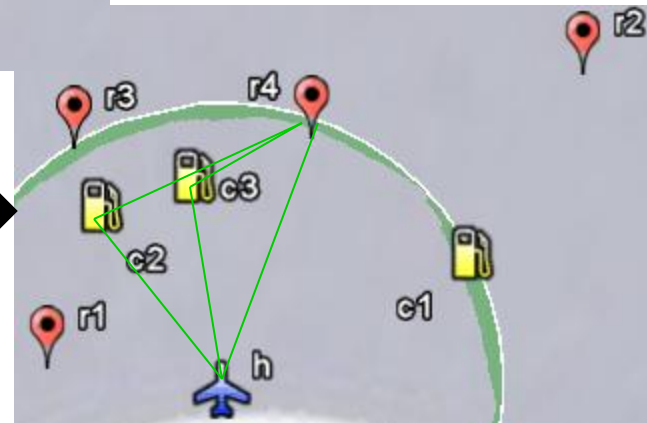


Fuel Consumed for r4
with cache c3
Research flight: 2844
Refueling flight: 1670
Upper bound: **4514**

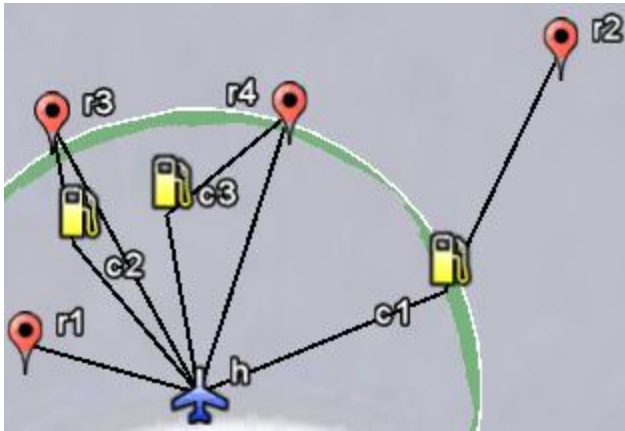


Min Fuel Consumed for r4

c1: ~~5776~~
c2: **3245**
c3: **2844**



Example continued



**Independent
Refueling
Flights**

vs.



**Global
Optimal**

Validation

- $N = \#$ research points
- $M = \#$ fuel caches
- Research Flights Only and Independent Refueling

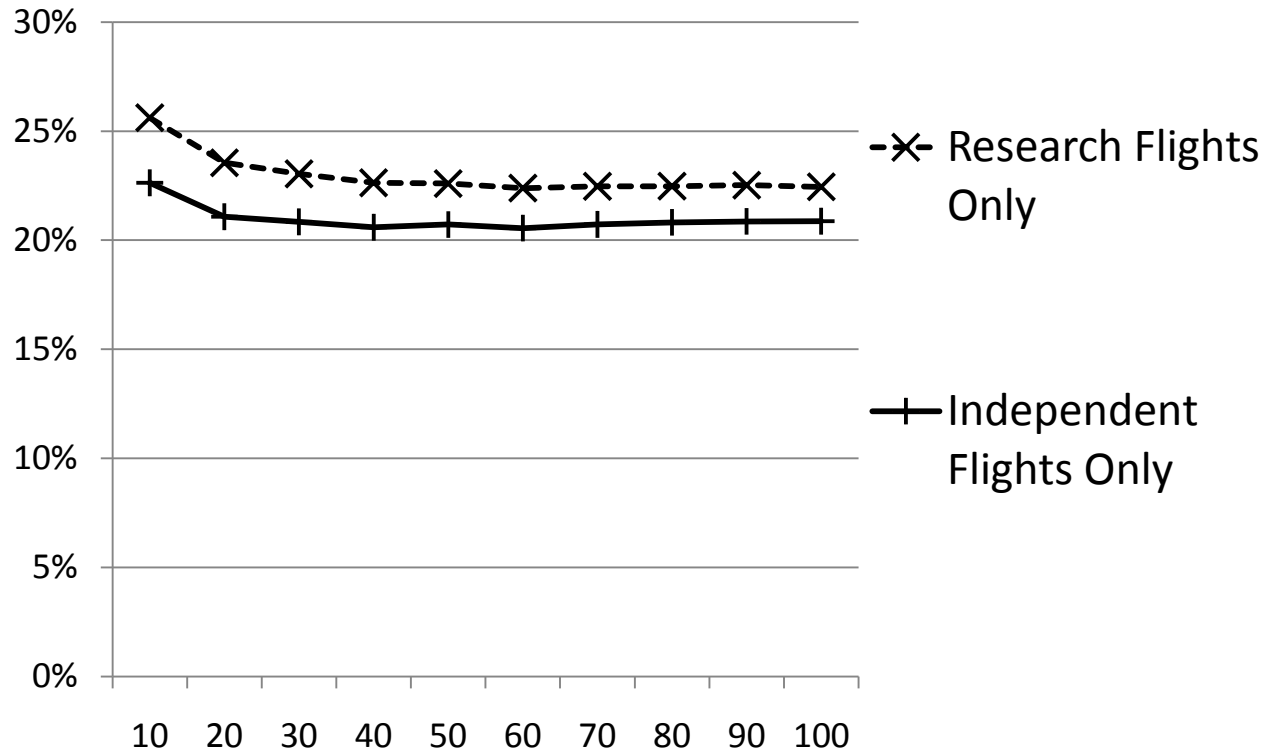
- Filter and Refine $O(N \times M)$
 - Worst case $O(M^N)$
 - Caches are tightly bunched so bound does not help
 - Best case $O(N \times M)$
 - One feasible cache per research point
 - Performs worst if caches tightly bunched
 - Generally not the case for problems of interest

Validation against current method

- Fuel required
 - Manual solution: 81405 lbs
 - Filter and Refine: 72118 lbs

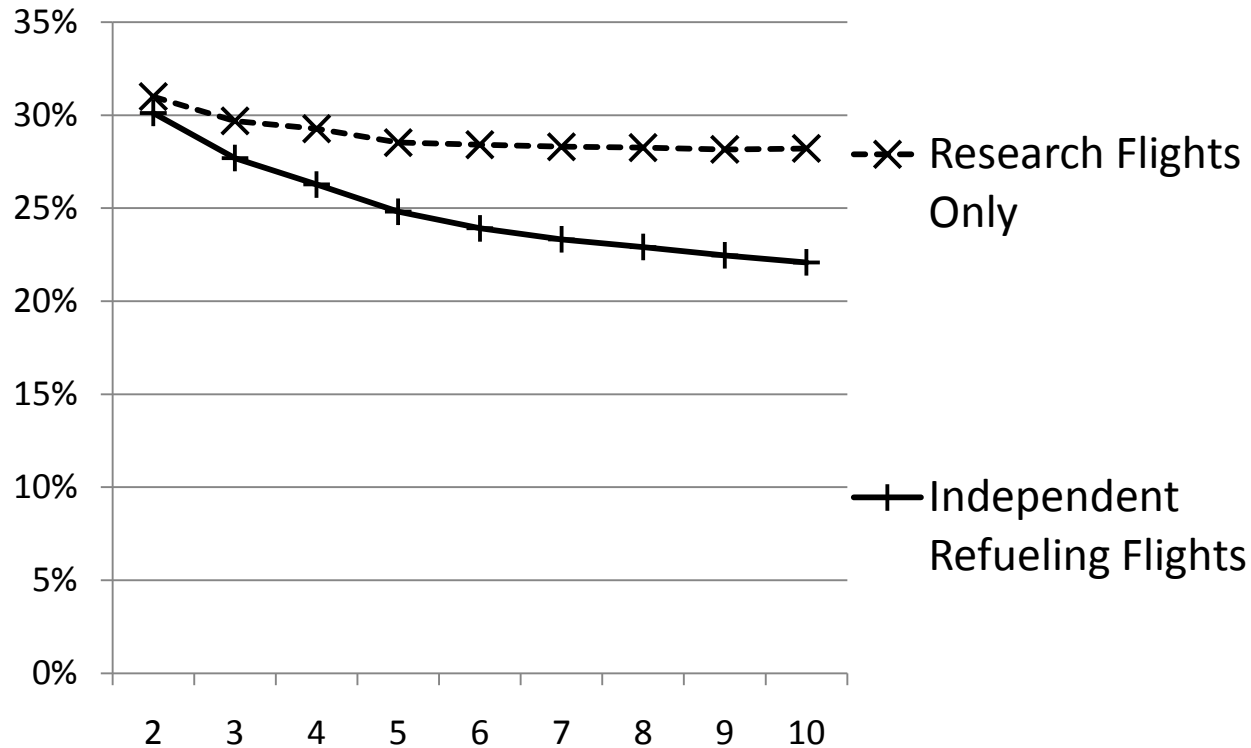
Step	Time for manual	Time for search
Step 1: Determine which research points need a refuel stop	10's of minutes	< 1 second
Step 2: Choose cache sites for each research point	1+ hours	10's of seconds
Step 3: Determine the amount of fuel to place at each cache site to support the refueling	10's of minutes	< 1 second
Step 4: Identify opportunities to consolidate fuel placement efforts by changing cache selections	1+ hours	-- part of step 2
Step 5: Recalculate fuel placement flights	10's of minutes	--

Simulated Results



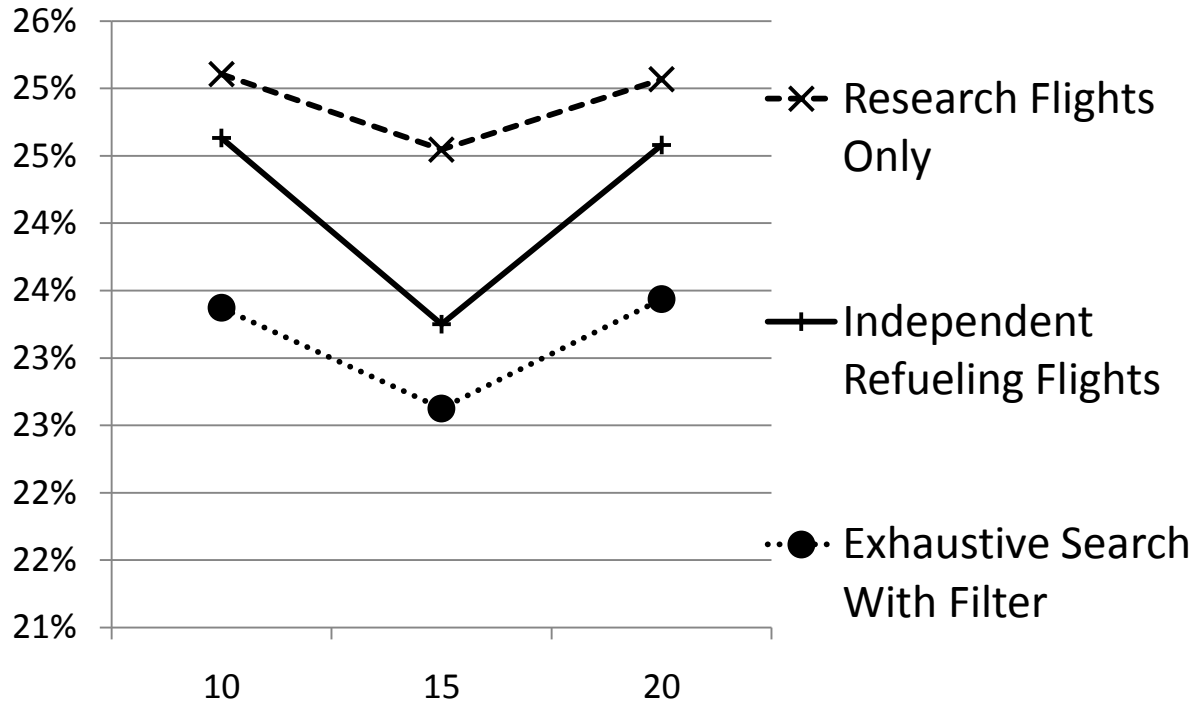
Percentage fuel costs contributed by refueling costs for problems with 4 fuel cache sites and 10 - 100 research points.

Simulated Results



Percentage fuel costs contributed by refueling costs for problems with 60 research points and 2 - 10 fuel cache sites.

Simulated Results



Percentage fuel costs contributed by refueling costs for problems with 2 fuel cache sites and 10 - 20 research points.

Simulated Results

Method	Average Execution Time		
	10 points	15 points	20 points
Research Flights Only	0.001 s	0.003 s	0.005 s
Independent Refueling Flights	0.003 s	0.050 s	0.063 s
Exhaustive With Filter	0.1728 s	22.7 s	1 hour *

* Min: 0.2 seconds, Max: 20 hours

Future Work

- More advanced algorithms for routing
 - Consider multiple caches
 - Alternate formulations such as Mixed Integer Programming
 - More advanced fuel consumption models
- Recommend fuel caches
 - Given existing flight plans, move fuel caches to optimize
 - Given research points, recommend fuel cache locations

Questions?